Chapter 11
Interface Design

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Abstract This chapter deals with different interface technologies that can be used to connect task-specific haptic systems to an IT system. Based on an analysis of the relevant bandwidth for haptic interaction depending on the intended application and an introduction to several concepts to reduce the bandwidth for these applications (local haptic models, event-based haptics, movement extrapolation, etc.), several standard interfaces are evaluated for use in haptic systems.

After the decision for the actuator (Chap. 9) used to generate the haptic feedback, and after the measurement of forces (Sect. 10.1) or positions (Sect. 10.2), it becomes necessary to focus on the IT interface. This interface has to be capable of providing data to the actuation unit and catch and transmit all data from the sensors. Its requirements result—such as with any interface—from the amplitude resolution of the information and the speed at which they have to be transmitted. The focus of this chapter lies on the speed of transmission, as this aspect is the most relevant bottleneck when designing haptic devices. Haptic applications are frequently located on the borderline, be it with regard to the delay acceptable in the transmission, or the maximum data rate in the sense of a border frequency.

With regard to the interface, two typical situations may be distinguished: spatially distributed tactile displays with a reasonable number of actuators and primarily kinaesthetic systems with a smaller number of actuators. In case of tactile systems, pin arrays, vibrators, or tactors, the challenge is given by the application of bus systems for the reduction of cable lengths, and the decentralization of control. Although there are still some questions of timing left, for example, to provide tactile signals in the right order despite a decentralized control, the data rates transmitted are usually not a challenge for common bus systems. Van Erp points out [6] that a 30-ms time delay between impulses generated by two vibrators at the limbs may not be distinguished any more. For the data interface, this observation implies for this application that any

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time delay below 30 ms may be uncritical for transmitting information haptically. This is a requirement that can be fulfilled by serial automation technology network protocols like CAN or the time-triggered version TTCAN, without any problems. Accordingly, this section concentrates on requirements of haptic kinaesthetic devices with a small number of actuators only, whereas these devices usually have to satisfy tactile requirements according to their dynamic responses.

11.1 Border Frequency of the Transmission Chain

Section 1.2.2 stated that it is necessary to distinguish two frequency areas when talking about haptic systems. The lower frequency range up to $\approx 30\,\text{Hz}$ includes a bidirectional information flow, whereas the high-frequency area >30 Hz transmits information only unidirectionally from the technical system to the user. Although the user himself influences the quality of this transmission by altering the mechanical coupling, this change itself happens at lower frequencies only, and is—from the perspective of bandwidth—not relevant for the transmission. If this knowledge is applied to the typical structures of haptic devices from Chap. 6, some fascinating results can be found. For the following analysis, it is assumed that the transmission and signal conditioning of information happens digital. According to NYQUIST, the maximum signal frequency has to be sampled at least two times faster. In practical application, this factor two is a purely theoretical concept, and it is strongly recommended to sample an analog system around 10 times faster than its maximum frequency. The values within figures and texts are based on this assumption.

11.1.1 Bandwidth in a Telemanipulation System

For a telemanipulation system (Fig. 11.1), the knowledge of the differing asymmetric dynamics during interaction gives the opportunity to benefit directly for the technical design. In theory, it is possible to transmit the haptic information measured at the

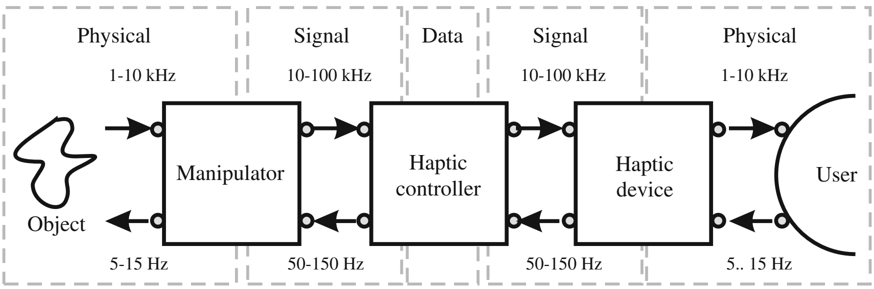

Fig. 11.1 Block diagram of a telemanipulator with haptic feedback

object within the bandwidth of 1 Hz–10 kHz, and replay it as forces or positions to the user. The user's reactions may in this case be measured at a bandwidth from static to 5 or 15 Hz only, and may be transmitted via controller and manipulator to the object. Although this approach would be functional indeed, the simplicity of position measurement and the necessity to process them, e.g., passivity control, result in movements being sampled and transmitted similar in dynamic as in the opposite transmission direction for haptic feedback.

11.1.2 Bandwidth in a Simulator System

For a simulation system with haptic feedback, the different dynamics result in slightly different findings. Nevertheless, it is still true that the movement information may be sampled at a lower rate. However, the simulator (Fig. 11.2) has to provide the force output at a frequency of 1–10 kHz. Due to this simple reason, the simulator has to be aware of the actual position data for every simulation step. Consequently, with simulators, the haptic output and the measurement of user reaction have to happen at high frequency (exceptions, see Sect. 11.2).

There are two approaches to integrate the haptic controller in the simulator. In many devices, it is designed as an external hardware component (Fig. 11.2), which reduces the computing load for the main simulator, and helps reducing the data rate significantly in special data processing concepts with parametrizable models (Sect. 11.2). As an alternative, the controller may be realized in software as a driver computed by the simulation main computing unit (Fig. 11.3). This is a concept used especially for high-power permanently installed simulation machines, or those used in cost-effective haptic devices for gaming industry with little requirements in dynamics and haptic output.

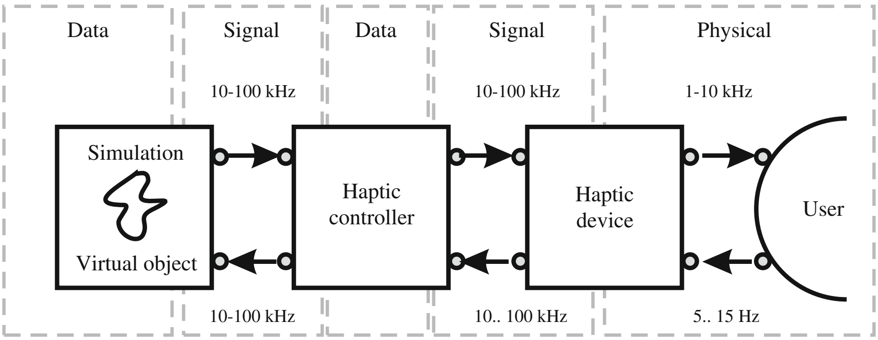

Fig. 11.2 Block diagram of a simulator with haptic feedback and an external controller

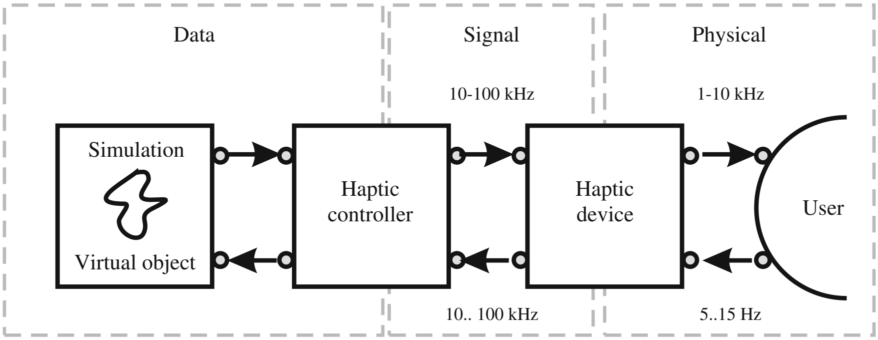

Fig. 11.3 Block diagram of a simulator with haptic feedback and a controller as part of the driver software

11.1.3 Data Rates and Latencies

Table 11.1 summarizes the data rates necessary for kinaesthetic applications in some typical examples. The data rates range from 200 kbit/s for simple applications up to 50 Mbit/s for more complex systems. Such rates for the information payload—still excluding the overhead necessary for the protocol and the device control—are achieved by several standard interface types today (Sect. 11.3).

Besides the requirements for the data rate, there is another requirement considering the smallest possible latency. In particular, interfaces using packets for transmission, with an uncertainty about the exact time of the transmission (e.g., USB), have to be analyzed critically concerning this effect. Variable latencies between several packets are a problem in any case. If there are constant latencies, the reference to other senses with their transmission channel becomes important: A collision is not allowed to happen significantly earlier or later haptically than visually or acoustically. The range possible for latency is largely dependent on the way to present the other sensual impressions. This interdependencies are subject to current research and are analyzed by the group around Buss at the Technische Universität München.

Table 11.1 Example calculating the required unidirectional data rates for typical haptic devices

DoFs	Resolution (bits)	0.1 kHz	1 kHz (kbit/s)	10 kHz
11 DoF	8	800 bit/s	8	80 kbit/s
	16	1,600 bit/s	16	160 kbit/s
13 DoF	8	24 kbit/s	240	2.4 Mbit/s
	16	48 kbit/s	480	4.8 Mbit/s
16 DoF	8	48 kbit/s	480	4.8 Mbit/s
	16	96 kbit/s	960	9.6 Mbit/s

11.2 Concepts for Bandwidth Reduction

Anyone who has tried to process a continuous data flow of several megabit with a PC, and in parallel make this PC do some other tasks too, will have noticed that the management of the data flow binds immense computing power. With this problem in mind and as a result of the questions of telemanipulation with remotely located systems, several solutions for bandwidth reduction of haptic data transmission have been found.

11.2.1 Analysis of the Required Dynamics

The conscious analysis of the dynamics of the situation at hand should be ahead of every method to reduce bandwidth. The limiting cases to be analyzed are given by the initial contact or collision with the objects. If the objects are soft, the border frequencies are in the range of <100 Hz. If there are stiff objects part of interaction and if there is the wish to feedback these collisions, frequencies up to a border >1 kHz will have to be transmitted. Additionally, it has to be considered that the user is limited concerning its own dynamics, or may even be further limited artificially. The DaVinci System (Fig. 1.10) as a unidirectional telemanipulator filters the high frequencies of the human movements to prevent a trembling of the surgical instruments.

11.2.2 Local Haptic Model in the Controller

A frequently used strategy being part of many haptic libraries is the use of local haptic models. These models allow faster reaction on the user's input compared to the simulation of a complete object interaction (Fig. 11.4). Such models are typically linearized functions dependent on one or more parameters. These parameters are actualized by the simulation at a lower frequency. For example, each degree of freedom of the haptic system may be equipped with a model of spring, mass, and damper, whose stiffness, mass, and friction coefficients are updated to the actual value at each simulation step, e.g., every $\approx\frac{1}{30}$ s. This approach does not permit the simulation of nonlinear effects in this simple form. The most frequent nonlinear effect when interacting with virtual worlds is the liftoff of a tool from a surface. Dependent on the delay of the actualization of the local model, the liftoff is perceived as "sticking," as the tools are held to the simulated surface by the local model in one simulation step, whereas it is suddenly released within the next. Concepts that model nonlinear stiffnesses compensate this effect satisfactorily. By making the additional calculations necessary for the local model, a significant data reduction between simulation and haptic controllers is achieved. Distantly related concepts are used in automotive

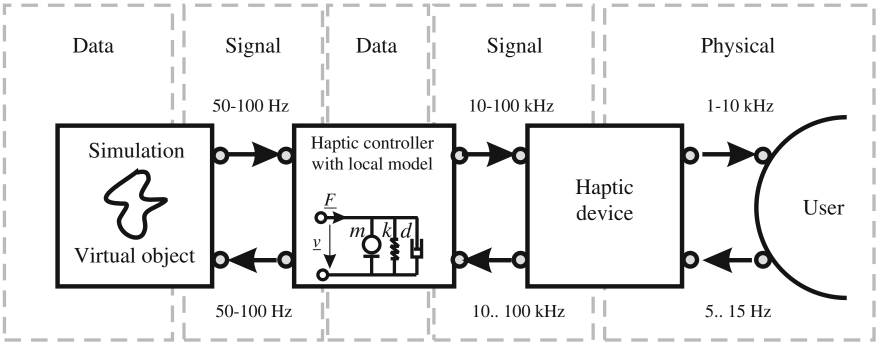

Fig. 11.4 Block diagram of a simulator with haptic feedback and a local haptic model inside the controller

applications, where CAN bus systems are configured in their haptic characteristics by a host, and report selection events in return only.

11.2.3 Event-Based Haptics

KUCHENBECKER presented in 2005 the concept of "event-based haptics" [2] and brought it into perfection since. It is based on the idea to split low-frequency interaction and high-frequency unidirectional presentation, especially of tactile information (Fig. 11.5). These tactile events are stored in the controller and are activated by the simulation. They are combined with the low-frequency signal synthesized from the simulation and are presented to the user as a sum. In an improved version, a monitoring of the coupling between haptic device and user is added, and the events' intensities are scaled accordingly. The design generates impressively realistic collisions with comparably soft haptic devices. As any other highly dynamic system, it nevertheless requires a specialized driver electronics and actuator selection to achieve full performance.

A variant of the concept of event-based haptics is the overlay of measured high-frequency components on a low-frequency interaction. This concept can be found in the case of VERROTOUCH (Sect. 2.4.4) or in the application of an assistive system like HAPCATH (Sect. 14.3). The overall concept of all these systems follows Fig. 11.6. A highly dynamic sensor (piezoelectric or piezoresistive) is implemented in a coupled mechanical manipulation system. The interaction forces or vibrations induced by collisions between tool and object are then transmitted to an actuating unit attached near to the handle of the device. In case of these systems, it is then just a variant whether the interaction path is also decoupled or sticks to the normal mechanical connection.

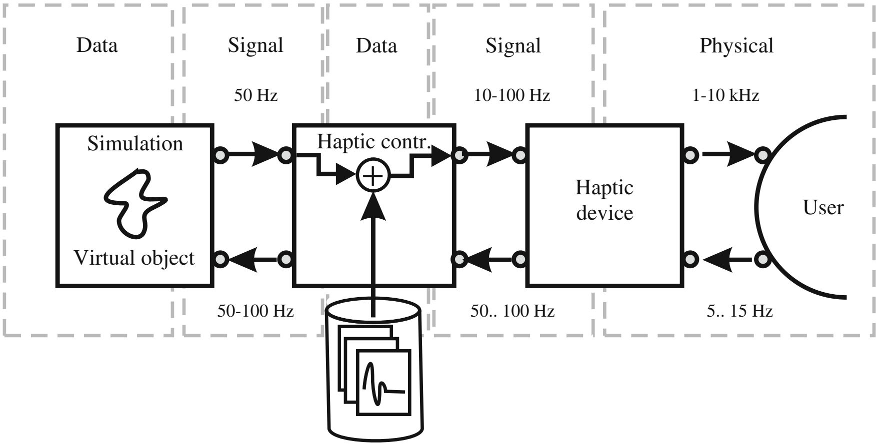

Fig. 11.5 Block diagram of a simulator with haptic feedback and with events of high dynamic being held inside the controlling structure

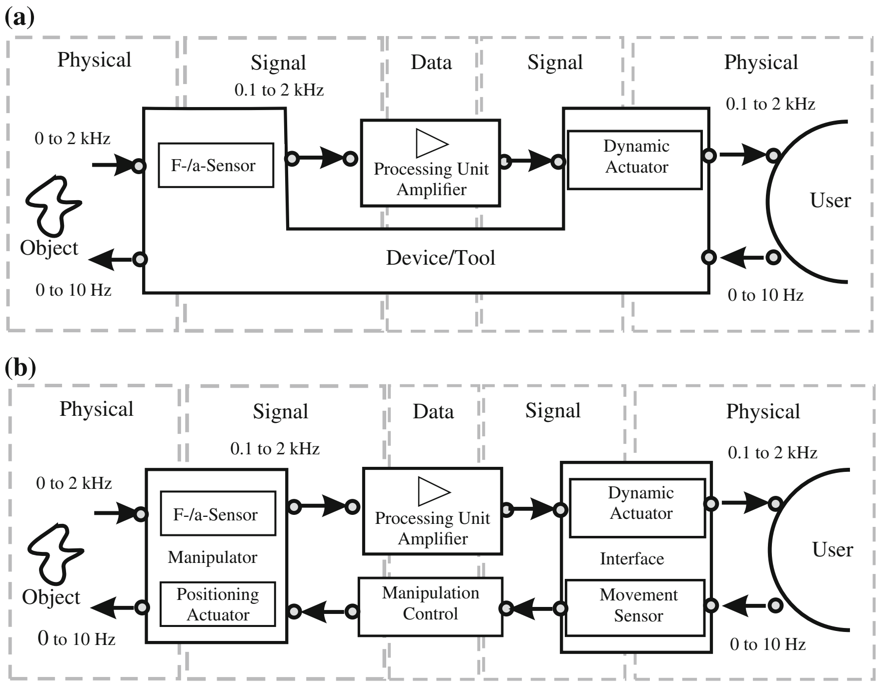

Fig. 11.6 Concept of an event-based haptic overlay of tactile relevant data with (**a**) and without (**b**) mechanical coupling of interface and manipulator

11.2.4 Movement Extrapolation

Another very frequently used method for bandwidth reduction on the path to measure user reaction is given by extrapolation of the movement. In particular, with simulators using local models, it is often necessary to have some information about steps in between two complete measurement sets, as the duration of a single simulation step varies strongly, and the available computing power has to be used most efficiently. The extrapolation becomes a prediction with increased latency and a further reduced transfer rate. Prediction is used for haptic interaction with extreme dead times.

11.2.5 Compensation of Extreme Dead Times

The working group of NIEMEYER from Telerobotics Laboratory at the Stanford University works on the compensation of extreme dead times of several seconds by prediction [4]. The dead time affects both paths: the user's reaction and the information to the user, such as the haptic feedback generated. The underlying principle is an extension of the telemanipulation system, which is added with a controller of the manipulator and a powerful controller for the haptic feedback (Fig. 11.7). The latter can be understood as an own simulator of the manipulated environment. During movement, a model of the environment is generated in parallel. If a collision happens in the real world, the collision is placed as a wall in the model, and its simulation provides a haptic feedback. Due to the time lag, the collision does not happen at the position where it happened in reality. During the following simulation, the collision point is relocated slowly within the model back to its correct position. By successive exploration of the environment, a more detailed haptic model is generated. The method has the status of a research project.

11.2.6 Compression

As any data stream, haptic data can be compressed for reducing their bandwidth. This may happen based on numerical methods on each individual packet; however, it may

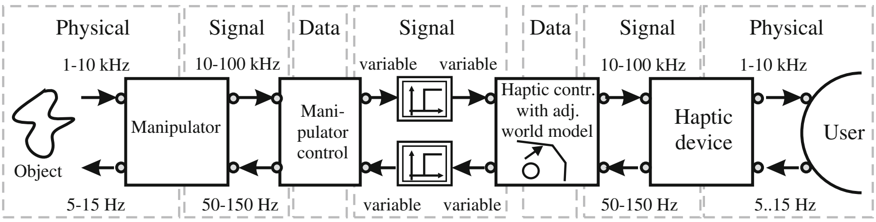

Fig. 11.7 Block diagram of a telemanipulator with compensation of long dead times by an adaptable world model

also be possible to make use of the special properties of the haptic human–machine interaction and haptic perception. The following list shall give a short overview about common approaches:

- A first approach for compressing haptic data is given in the situational adaption of digitalization on the path for measuring user reaction. SHAHABI ET AL. [5] compare different digitalization methods adapting their time and amplitude discretization on the actual movement velocity.
- Since several years now the working group around BUSS does intensive research on the perceptional impact of loss of resolution and bandwidth in haptic data streams [3]. They are coupling their research with the analysis of user reactions and basing their algorithm on the psychophysical perception and a benefit–effort analysis.
- The working group around EL SADDIK wants to achieve data reduction by standardizing the haptic interaction in a descriptive data format "HAML". It models the environment in a comparably little set of parameters, which gives advantages in teleinteraction applications with a larger group of participants. In particular, varying data transmission paths can be compensated more easily on this abstract description, in comparison with classic telemanipulation approaches with a transmission of explicit forces and positions. As a by-product of this work, concepts for the unidirectional replay of haptic data in the form of a "haptic player" are developed [1].
- Another obvious approach for compression is the usage of limitations given by haptic perception. The working group of KUBICA demonstrates [7] an analysis of an interaction with a virtual environment at different velocities. The identified dependency of the force perception threshold on the velocity was successfully used as a basis for data reduction.

11.3 Technical Standard Interfaces

Most haptic devices are operated with personal computer or related systems. They offer a high flexibility in configuration as well as for research projects as for gaming and design applications. Within this section, different standard interfaces typical to PC hardware architecture are highlighted and discussed with respect to haptic device applications.

11.3.1 Serial Port

The serial port is an interface, which is—dependent on the operating system used[1]—quite simple to be addressed. The serial interface of a home computer is based on the

[1] As a rule of thumb: with Linux or DOS systems, a direct communication using the serial interface is lot simpler when compared to Windows operating systems.

RS232 standard. This standard defines, besides several timing aspects, the bits being encoded in between ±3 to ±15 V for low and high levels. A connection to digital circuits with different logic has to happen via a converter, such as the MAX232. Usually, only two lines (RxD and TxD) are necessary for data transmission. The maximum specified data rate is 20.000 bit/s, whereas data rates far off specifications with 56 or 128 kbit/s are also possible. Both the data rate and the number of bytes carrying the actual data payload can be configured in a wide range. Two systems communicating with each other have to be adjusted in these parameters. A simple parity control with one bit is also integrated. With respect to its data rate, the serial port is absolutely suitable for the control of simple haptic devices. However, due to its master–slave architecture, a bidirectional data communication is connected with a large data overhead as a result of the coordination of both units. As modern PC is not necessarily equipped with serial ports only, several USB-to-serial converters are offered at the market. They emulate a COM port in software and transmit the data through the USB connector and the typical 9-pole socket. The data rates achievable with these connectors are usually sufficient, but they show some unpredictable delays and time loss due to software emulation of the interface. This makes them hardly usable for time-critical haptic applications.

11.3.2 Parallel Port

The parallel port is, if it is still part of modern PCs, a 25-pole double-row SUB-D-socket on the computer back plane. Similar to the serial interface, its ease of use is largely dependent on the operating system. In an ideal case (with several Linux distributions and with DOS), the address of the port can be directly written with three consecutive bytes. In this case, the first byte represents the eight data lines and the two following bytes are used for setting and reading of the control lines. The parallel port is set to work with 5 V logic levels with a maximum source current of ≈5 mA and sinking currents of maximum ≈20 mA. An overload current or leveling the pins to wrong voltages should be strictly avoided, as typical PCs do not show any protective circuitry. The data transmission of modern parallel ports is usually bidirectional, allowing read and write operations on the same eight data lines. But as the change between data transmission directions needs some time, the control lines are frequently used as input, whereas the data lines operate as output. Writing to and reading from the port can be made with frequencies up to 100 kbit/s without much effort. An extension of the parallel port is given by the "Enhanced Parallel Port" (EPP) and the "Enhanced Capabilities Port" (ECP). Whereas the ECP excels by Plug and Play functionalities mainly, the EPP had been designed for an increase in bidirectional data transmission rates up to 2 Mbit/s. This increase was achieved by a hardware implementation of the data protocol. For a slave using the EPP—such as a haptic device—this additional hardware requires of course some more hardware on the device's end, as the protocol has to be realized near to the interface. From the perspective of data rates, the parallel port is highly suitable for haptic devices, especially in EPP mode. In particular, low latencies of $<100\,\mu s$ between writing command and the availability of the data make it very attractive. Only the dwindling availability of this port to standard PCs makes it necessary to use other type of interfaces.

By their flexibility in software drivers, the serial and the parallel port makes it possible to be interfaced as debugging ports to microcontroller circuits or to bus systems such as I2C or CAN.

11.3.3 USB

The USB port is a serial port with a predefined data transmission protocol. It contains two data lines, an electrical ground, and a 5-V supply, which can be drained with up to 100 mA per device attached. According to the USB specifications, this load can be increased up to 1 A, if the host accepts it. An extension of the standard named "power USB" considers additional lines for higher currents and even larger voltages. The USB clients receive an identifier when being connected to the bus, which marks the data packages, sent to or from them. Each USB component has "device descriptor" uniquely identifying the manufacturer and the product. Additionally, each device is classified into several standard classes. The "human interface device class" (HID) is reserved for input systems. Devices with active, haptic feedback are grouped in an own class of "physical interface devices" (PID). Each manufacturer of a USB driver circuit has to apply for a unique product id. Due to the requirements and the complexity connected to the implementation of a USB conform protocol, it is recommended to use USB interface circuits off the shelf for product designs with little quantities manufactured. Such interface circuits offer parallel or serial data lines to be interfaced by an own microcontroller, which itself does not have to bother about the USB interface any more. The USB interface can be operated in different modes. For the transmission of larger, time-critical data volumes, the "isochrone" transfer is the most suitable. Its theoretical limit is given by the data packets, which are transmitted in microframes according to the USB 2.0 standard. The duration of a microframe is given by $125\,\mu s$. So-called full-speed systems are able to transmit up to 1,023 bytes with each microframe. High-speed devices are able to transmit even three times more bytes per microframe. According to the specifications, transmission rates of up to 40 MByte/s are possible with devices combining several isochronous endpoints in one unit. The data rate of isochronous transfer is optimized for unidirectional transmission only. In case of bidirectional communication, the data rate is reduced accordingly. Nevertheless, the speed of the USB port covers any requirements given by USB devices. However, two special aspects have to be checked in the context of the individual application:

- A microframe of $125\,\mu s$ duration (8 kHz) is the upper limit of the available bandwidth. Without compression and decoding, this gives the natural bandwidth limit according to NYQUIST of 4 kHz.
- The data rate has a tolerance of 0.1 %.

11.3.4 FireWire: IEEE 1394

FireWire, Apple's brand name, according to the IEEE 1394 standard is a serial transmission format similar to USB. In fact, it is a lot older than the USB specification. The six-pole FireWire Connector includes a ground and a supply line. The voltage is not controlled and may take any value between 8 and 33 V. FireWire 400 defines up to 48 W power to be transmitted. The data rates are—dependent on the port design—100, 200, 400, or 1,600 kbit/s. This is completely sufficient for any haptic application. Even fiber optics transmission over 100 m distance with up to 3,200 kbit/s is specified in the standard. The bus hardware additionally includes a concept to share memory areas between host and client, enabling low-latency transmissions. Even networks without an explicit host can be established. The interface according to IEEE 1394 is the preferred design for applications with high data transmission rates. Only the little propagation of this interface in personal computers hinders a wide application.

11.3.5 Ethernet

The capabilities of the Ethernet interface available with any PC are enormous but largely dependent on the protocol used. Whereas the naked interface enables transmission rates of 10 or 100 Mbit or even gigabit, the available data payload within the transmission is largely dependent on the interlacing of the underlying protocols. The very well-known TCP/IP protocol has a header portion of 40 bytes. The Ethernet protocol adds another 18 bytes for the Ethernet frame, and some more 8 bytes for the whole packet, resulting in an overhead per packet of 66 bytes. This packet may contain up to 1,460 bytes of data. This is sufficient for typical haptic applications with respect to the available space per packet. Assuming a six-DOF kinematics with 16 bit (2 byte) resolution in their sensors and actuators, each packet has to carry only 12 bytes of data, with one packet for force output and one for position input. The number of bytes carried in each packet has a lower limit depending on the physical design of the network. In the area of home networks, it is 50 bytes, making it necessary to add arbitrary data on the example from above. A cycle of the haptic device example would transmit 232 bytes, which is 1.856 kbits. With a 10-Mbit network, theoretical bandwidth of 8 kHz would be available. Even when considering that the data have to be extended with some additional overhead (address negotiations, status information), this is still sufficient for many haptic applications. A disadvantage in using the Ethernet is given by the high efforts necessary for packet confection and protocol formulation, which would usually overload the computation power of standard microcontrollers. Additionally, a high number of clients reduce the data rate within a network significantly. Using switches compensate this reduction to some extend. But the method of choice is usually given by an exclusive network for the haptic application.

11.3.6 *Measurement Equipment and Multifunctional Interface Cards*

Measurement and multifunction interface cards are a simple approach to interface to hardware designs. They are available for internal and external standard interfaces, such as PCMCIA, USB, or even LAN. They are usually equipped with several standard software-drivers optimized for their hardware capabilities. When considering a prototype design, they should be considered in any case. Their biggest disadvantage is given by the data processing happening inside the hosting PC and within the restrictions of the operating system. In particular, in combination with non-real-time operating systems like Windows, the dynamics of controllers necessary for haptic applications may become not fast enough.

11.3.7 *HIL Systems*

"Hardware-in-the-loop" (HIL) systems were first used in control engineering and to compensate the disadvantages from multifunctional cards for rapid prototyping and interfaces to haptic systems. HILs include a powerful controller with proprietary or open real-time operating system. The programs operated on these controllers have to be built on standard PCs and are transmitted as with any other microcontroller system. Frequently, the compilers allow programming with graphical programming language such as MATLAB/Simlink or LabView. The processors of the HILs are connected via specialized bus systems with variable peripheral components. Ranging from analog and digital output over special bus and actuator interfaces, a wide range of components is covered. HIL systems are predestined for the always time-critical applications of haptics in design phase. But compared to other solutions, they have a high price.

11.4 Final Remarks on Interface Technology

The interface subordinates to the requirements of the system. Any realistic application and its required data rate can be covered with today's standard components. Only commercial or company interests may prevent the choice of a suitable interface for a haptic device. This is a complete difference to the situation at the beginning of the twenty-first century. At this time, highly specialized interfaces were designed for haptic devices, to cover the high requirements on data transmission rates. Accordingly, even today, commercial products with own ISA or PCI interface cards can be found on the market. Other solutions require an EPP parallel port still. Nevertheless, the design of controller circuit suitable for the USB protocol should not be underestimated. In particular, its layout and programming for the still high data rates of haptic devices offer enough room for errors. Although the technical specifications are sufficient to fulfill the requirements, the first design and operation is far from being trivial.

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