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CHAPTER 8

Energy Created by a Delayed Channel in a Bilateral Teleoperation Simulator

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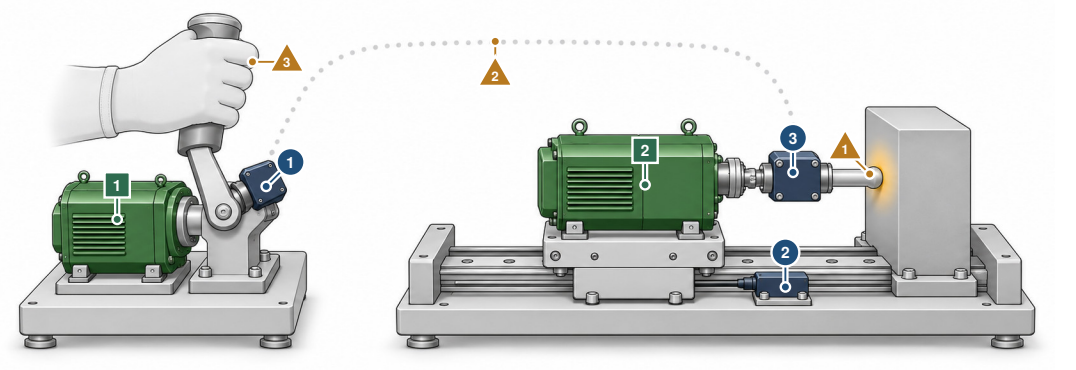
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CHAPTER 8

Energy Created by a Delayed Channel in a Bilateral Teleoperation Simulator



The controller moves 1 motors on the master handle 2 slave drive on the carriage

The controller reads 1 master handle position 2 slave carriage position 3 force sensor at the tool

What disturbs it 1 wall nearer or farther than its drawing 2 longer delay, lost packets 3 operator pushes harder

The handle and the slave share nothing but the delayed link drawn dotted, so the force the tool meets at the block reaches the hand late. Illustration, not to scale.

IN PLAIN TERMS **Feeling a Wall Through a Slow Link**

The main idea. A person moves a handle, and a robot far away copies the motion. When the robot touches a wall, its push is sent back to the handle, so the hand feels the wall too.

The challenge. The link takes time, so the push arrives after the hand has already moved on. The late push can shove the hand back and make the robot bang the wall, adding energy that no part of the machine put in.

Why it matters. Each fix for this costs something: a softer wall, a robot that lags the hand, or a guess about the wall that can be wrong.

THREE WAYS TO READ THIS CHAPTER

Explore	11 min	the first page, the fact on the Moon's delay (Section 8.1), the two history segments (Section 8.2), the two try-its and the fact on move and wait (Section 8.6) and the key points
Study	50 min	the whole chapter with its three pause points and the twelve exercises at its end
Practice	15 min	the first page, the results (Section 8.6), Technology in Practice (Section 8.7), Limitations (Section 8.8) and the two open challenges

The control question When a slave's contact force is sent back through a delayed link, the feedback that makes a remote wall feel solid can make it chatter, although the hand, the devices and the wall are each passive. Where does the energy come from, and what does each cure for it cost in feel, position or knowledge?

Learning objectives

- Explain how a delayed channel creates energy at its two ports, and read the ledger that measures it.
- Compute the gain limit K_h/K_{ser} of force reflection through a long delay, and say when the running model's verdict can miss it.
- Estimate the wall that wave variables render from the wave impedance and the delay.
- Compare wave variables, a time-domain passivity controller and model mediation on the same task by stability, felt stiffness, position and task time.
- Judge whether a contact that keeps still proves a passive channel.

Prerequisites Sections 1.4.2, 1.4.3, 1.6 and 1.6.4.

The app https://apmonitor.com/apps/teleoperation-delay/

See also Volume 20, Chapter 13 for a peg pushed into a chamfered hole under force control, Volume 20, Chapter 14 for a teleoperated console that scales motion and filters tremor, and Volume 7, Chapter 14 for the same delayed, lossy channel and a gain that must stay below one at every frequency.

8.1 Introduction

A teleoperator lets a person work where a person cannot go, inside a shielded cell, on the sea floor, inside a patient or on another world. The person moves a master and a slave copies the motion at the remote site. When the slave's contact force is sent back and rendered on the master, the hand feels the remote wall, and the interfaces between the operator and the master and between the slave and its environment become ports through which the teleoperator exchanges energy [1]. A transatlantic robot-assisted operation in 2001 [2] and a ground station that worked a satellite's arm bilaterally through a round trip of about 7 s in 1999 [3] put long links between the hand and the work.

DID YOU KNOW? Six to Eight Seconds to the Moon and Back

In NASA studies of 2023, operators on Earth drove a simulated lunar rover through round trips of 0, 4, 6 and 8 s, driving slower and braking more often under a delay. The mission's communications team now estimates the round trip at 6 to 8 s [4]. Case 9 assumes 2.6 s.

The delay in that link is what sets the problem apart. The hand, the master, the slave and the wall can each only store or dissipate energy, but a channel that returns the slave's force after a delay pairs it with a velocity it never met, and the pair can put out energy that no element put in. Passivity and scattering theory showed why existing bilateral systems are unstable for certain environments [5]. In the simulator of this chapter, force reflection with no delay holds 3.06 N at the wall for 3.06 N on the handle, and its energy ledger books 0.78 mJ over three presses. Given 100 ms of round trip, the same loop bounces off the wall every 0.33 s, and the channel has created 34.1 mJ by the end of the first touch and 15.5 J over 30 s. No element changed, so the energy came from the channel, and a model of the slave with a dead time appended, however exact, could not have shown where it came from.

Three expectations a student brings to this plant fail on it, each by a measured amount. Lowering the reflection gain is expected to trade a little feel for stability, yet the sampled loop, linearized in contact, keeps full reflection stable only below a round trip of about 10 ms, and at 500 ms only below a gain of 0.2245, so that at 0.20, the largest setting of the gain slider below that limit, a press of 3.75 N on the handle drives the peg into the wall at 23.7 N. A contact that keeps still is taken as proof of a passive channel, but at 100 ms and a gain of 0.30 the contact keeps still while the channel creates 110 mJ, and even with no delay a gain of 0.5 creates 12.2 mJ. A cure that makes the channel passive is

expected to cost little, although wave variables, which never create energy at a constant delay, render the wall at 173 N/m against 1243 N/m without delay, and through a dropout a held wave leaves the peg pressing the wall 30.4 mm ahead of the master.

Teleoperation is one member of a wide family. Two dynamic systems that exchange force and motion across a delayed or sampled link can turn the interface between them into a source of energy, and the stability of the pair then rests on the interface's energy books rather than on either system alone. Haptic interfaces that render stiff virtual walls are held stable by the same bookkeeping, demonstrated with 15 ms of delay [6], telemanipulation over the Internet meets delays that vary [7], and networked control systems in general contend with sampling, network delay and packet dropouts [8]. A congestion controller whose dead time is the round trip of the network path it regulates is the subject of Volume 2, Chapter 7.

However, each remedy for delay was demonstrated on its own hardware and judged by its own measure, the completion time of a task, the stability of a contact or the feel of a wall [3, 9–11], and no common bench books the energy of every architecture in one way, whether or not its controller looks at energy. This chapter locates the source of the energy a delayed force-reflecting loop creates, on a teleoperation simulator whose channel carries a ledger at its two ports, and it prices each passivity remedy in feel, position and knowledge. Every architecture used comes from the literature. The teleoperator is described completely enough to be rebuilt. Its two sides learn of each other only through seeded links, its ledger multiplies the same forces and velocities the controllers exchange, and its operator perceives the wall through a filtered feel and a delayed video. The loop is linearized as the application samples it, and the gain limits are compared with the running model. Nine cases and a graded challenge isolate the delay, the gain, the architecture, the network and the model.

Section 8.2 follows remote manipulation from the hot cell to model mediation. Section 8.3 builds the devices, the site, the channel with its energy ledger and the scripted operator, and Section 8.4 the four architectures and the passivity controller, period by period. Section 8.5 derives the gain limit of force reflection through a delay and checks it against the running model. Section 8.6 reports what each case and the challenge measured, Section 8.7 sets the teleoperator beside real sensors, links and practice, Section 8.8 states the limitations and Section 8.9 draws the conclusions.

8.2 From Hot Cells to Wave Variables

Remote manipulation began behind radiation shielding, in the hot cell, with the mechanical master-slave manipulator that the history segment below describes. The experiments of the 1960s separated the two sides by a transmission delay.

> ⧖ HISTORY **1949: Tongs That Followed a Handle**
>
> A report from Argonne National Laboratory dated March 1949 described a device, built and tested, for handling a pair of tongs behind a shielding barrier such as a lead glass window. It was named a master-slave manipulator because the slave tongs moved in exact correspondence with a master handle about three feet away. The test model was entirely mechanical: seven independent linkages of tubes, gears, drums and cables carried three straight motions, three rotations and the closing of the jaws. Most people learned to work it within five to fifteen minutes. Friction and mass in all seven motions had to be kept very low, and backlash impaired operation. The report called it the first completely master-slave manipulator known to exist [12].

Those experiments measured task time. A study of 1963 described several manipulator devices, reported an experiment on the effect of delay on the completion time of a simple manipulative task, and found that under certain circumstances the time with delay could be predicted from measures of performance taken without it [13]. Two years later most operators faced with a delay spontaneously adopted a move-and-wait strategy, and the completion time depended on the number of open-loop moves, which a simple statistical model predicted from the difficulty of the task [14]. Force feedback

was tried next. With long delays, positioning by force feedback alone was possible, but delay coupled with a high loop gain created serious instability, and alternative displays of the feedback force overcame it [9].

Space gave the delay its size. A review of 30 years of research on delay in human teleoperation in space described the experiments on human performance, predictive displays that help the operator overcome the delay, supervisory control ranging from local impedance control on contact to higher-level automation, and wave transformations, and it observed that space teleoperation had tended to avoid the delay by not teleoperating from the ground [15]. In November 1999 a ground station teleoperated the arm of the Engineering Test Satellite 7 bilaterally through a round trip of about 7 s, with a teleoperator built to stay stable through it, and slope-tracing and peg-in-hole tasks showed that kinesthetic force feedback improved performance even at that delay [3].

The account of why delayed force reflection fails came from network theory. A hybrid two-port model treated the interfaces with the operator and with the environment as ports through which the teleoperator exchanges energy, and compared measured or simulated systems with the ideal one [1]. Passivity and scattering theory then explained why existing bilateral systems were unstable for certain environments and gave a law that is stable for any environment and any time delay [5]. Wave variables gave that idea a physically motivated, passivity-based formalism with energy conservation and stability guarantees in the presence of transmission delays [16]. A general architecture that transmits force and velocity in both directions showed that transparency and robust stability (passivity) are conflicting design goals [17], and later work examined the wave reflections and spurious dynamics of passive transmission and laid the basis for applying wave variables to the variable delays of Internet-based telemanipulation [7].

> ⧖ **HISTORY** **1989: The Operator's Arm Sets the Limit**
>
> A paper at a NASA conference on space telerobotics in 1989 modeled bilateral force reflection on one axis for a space robot then in development. In its model the operator's arm and the hand controller play the part that a programmed filter plays in impedance control. The analysis showed that delays as small as 10 ms, from communication or computation, can significantly raise the stiffness and damping the operator must supply to keep the loop stable, and that stiff work pieces raise them further. Tests of five subjects found the operator's stiffness and damping tightly coupled. Scaling the force or position gains can stabilize any such system, the paper concluded, but at the cost of reducing the feel to the operator [18]. The bound of Equation (8.15) makes the same point for this chapter's hand.

Time-domain passivity control replaced the frequency-domain guarantee with bookkeeping. A passivity observer measures the energy flowing in and out of a subsystem in real time, and a passivity controller, an adaptive dissipative element, absorbs at each sample exactly the net energy output the observer measures, which kept a haptic interface stable above 100 N/mm of stiffness or with 15 ms of delay [6]. The method was extended to the two-port network of a teleoperator, stable in contact with a hard wall above 150 kN/m [10], and to communication delays that vary in time [19]. Model-mediated teleoperation went the other way. Instead of sending the slave's sensory data, the slave abstracts it into a simple model of the environment that the master renders without lag, and the slave executes only commands consistent with the model, shown on a one-degree-of-freedom system with 4 s of round-trip delay [11]. The simulator of this chapter books the energy at both ports for every one of these architectures, whether or not its controller uses energy, from the forces and velocities its two controllers exchange.

8.3 The Teleoperator, Its Channel and Its Site

The two devices appear along one axis in Figure 8.1(a) and the site they work on from above in Figure 8.1(b). Master and slave move in one shared frame, in meters, with x running across the wall and y toward it, and their two axes are independent. The integrated state has ten entries, the master's

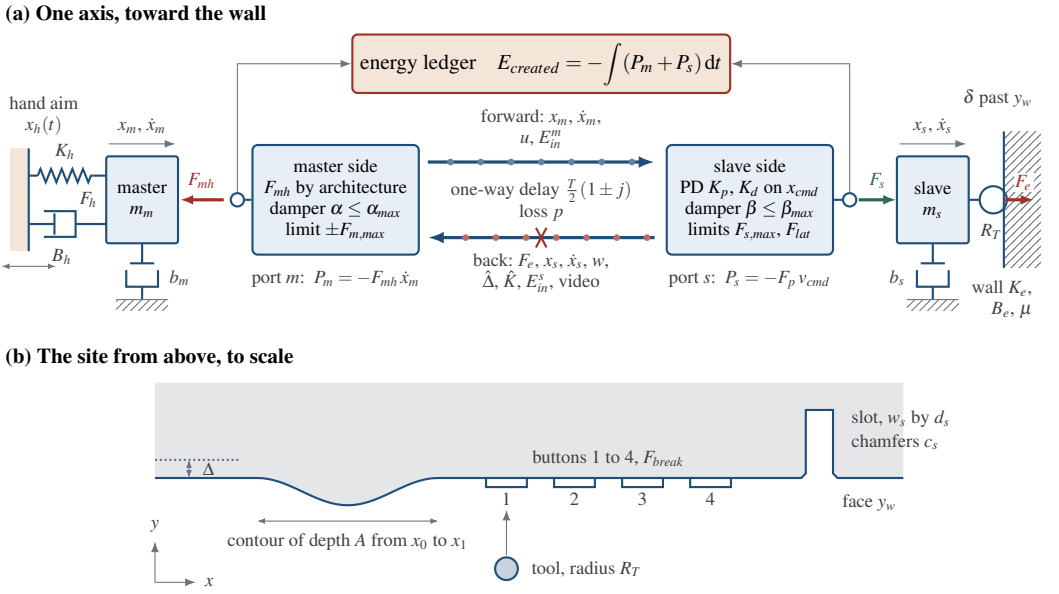


Figure 8.1 The teleoperator modeled by the application. (a) One axis, toward the wall. The hand is a spring K_h and a damper B_h about its aim $x_h(t)$ and pushes the master handle m_m, damped by b_m, while the master's motors push back with F_{mh}. Two links carry one packet each way every millisecond, with a one-way delay that wanders within $\pm j$ of $T/2$ and a loss probability p. The slave drive F_s, a PD on the delayed command limited to $F_{s,max}$ and to F_{lat} across the wall, moves the carriage m_s, damped by b_s, whose tool of radius R_T meets a wall of stiffness K_e, damping B_e and friction μ with the force F_e at a penetration δ past the face y_w. The ledger integrates the power P_m and P_s entering the channel at its two ports. (b) The site in the slave's frame, to scale: the face with its contour bump, four buttons 4 mm proud of it and the slot with its chamfers. The dotted line is the drawing that the operator and the model's prior start from, which in case 7 lies 8 mm beyond the real face, a site offset $\Delta = -8$ mm.

position and velocity $\mathbf{x}_m = (x_m, y_m)$ and $\dot{\mathbf{x}}_m$, the slave's $\mathbf{x}_s$ and $\dot{\mathbf{x}}_s$, and the friction bristles z_L and z_R of the two wall blocks beside the slot, and Table 8.1 classifies the signals. Whatever is discrete, the clicks of the buttons, the seating of the peg, the slip of a bristle, the count of reversals and the oscillation flag, is handled between integration steps and kept out of the derivative function.

8.3.1 The Devices

The master is a mass under the hand and its motors, and the hand is a spring and a damper about the point it aims at, as shown in Equation (8.1).

$$\begin{aligned} m_m\ddot{\mathbf{x}}_m + b_m\dot{\mathbf{x}}_m &= \mathbf{F}_h + \mathbf{F}_{mh} \\ \mathbf{F}_h &= K_h(\mathbf{x}_h - \mathbf{x}_m) + B_h(\dot{\mathbf{x}}_h - \dot{\mathbf{x}}_m) \end{aligned} \tag{8.1}$$

where $\mathbf{x}_h$ is the hand's aim and $\mathbf{F}_{mh}$ the force the motors put on the handle, both held over each 1 ms control period, and b_m is the handle's friction together with the damping its own controller adds. The slave carriage obeys Equation (8.2).

$$m_s\ddot{\mathbf{x}}_s + b_s\dot{\mathbf{x}}_s = \mathbf{F}_s - \mathbf{F}_e \tag{8.2}$$

where $\mathbf{F}_s$ is the drive force and $\mathbf{F}_e$ the force the tool exerts on the site, which the slave's force sensor reads. The two sides share one frame at one scale, so a position on the master is the position it commands at the site.

Table 8.1 Signals of the Teleoperator by Role, With Their Defaults

Symbol	Role	Default	Range
$\mathbf{x}_m$, $\dot{\mathbf{x}}_m$	states, master handle	at the start	site
$\mathbf{x}_s$, $\dot{\mathbf{x}}_s$	states, slave, CV of its PD	at the start	site
z_L, z_R	states, friction bristles	0	$\lvert z\rvert \le \mu F_n/K_t$
$\mathbf{F}_{mh}$	MV, master motors, held 1 ms	0	±20 N an axis
$\mathbf{F}_s$	MV, slave drive, held 1 ms	0	±50 N, F_{lat} in x
$\mathbf{x}_h$	hand's aim, the student's in MANUAL	at the start	site
T, j, p	channel round trip, jitter, loss	0, 0, 0	to 2.6 s, 20, 20 %
—	DV, operator pushes harder	100 %	100–300
Δ	DV, site offset from its drawing	0	±15 mm
w_K	DV, wall stiffness over nominal	100 %	50–400
—	DV, slave drive capacity	100 %	0–100
—	DV, satellite hop, loss burst	events	+500 ms, 1 s
$\mathbf{F}_e$	measured, slave force sensor	—	—
$\bar{F}_h$	perceived, felt force over 50 ms	—	—
P_m, P_s, $E_{created}$	outputs, the energy ledger	0	—

8.3.2 Contact With the Site

The tool is a disc of radius R_T seen end-on. The site is the solid beyond the face $y > y_f(x) + \Delta$, with Equation (8.3).

$$y_f(x) = y_w - A\sin^2\left(\pi\,\frac{x - x_0}{x_1 - x_0}\right), \qquad x_0 < x < x_1 \tag{8.3}$$

and $y_f = y_w$ elsewhere, interrupted by the slot. Seven bodies can touch the tool, the two wall blocks on either side of the slot (each its face, its chamfer and its slot wall, convex near the slot so that each makes one contact), the slot bottom and the four buttons. For each body i the penetration is $\delta_i = R_T - d_i$, with d_i the distance from the tool's center to the body, signed negative inside it, and $\mathbf{n}_i$ the unit normal from the body toward the tool. The rigid bodies push back with Equation (8.4).

$$F_{n,i} = \max\Big(0,\ w_K K_e\,\delta_i + B_e\,\dot{\delta}_i \min\left(1,\ \delta_i/\delta_r\right)\Big) \tag{8.4}$$

where $\dot{\delta}_i$ is the rate of penetration along $\mathbf{n}_i$, w_K the wall stiffness disturbance, and the damping fades in over the first $\delta_r = 0.5$ mm so the force is continuous at the instant of touch. A button is a plate 4 mm proud of the face whose penetration δ is its travel, and its snap spring is Equation (8.5).

$$f_b(\delta) = \begin{cases} F_{break}\,\delta/p_c, & \delta < p_c \\ F_{break} - (F_{break} - F_{low})\,\dfrac{\delta - p_c}{p_s}, & \delta < p_2 \\ F_{low} + (F_{bot} - F_{low})\,\dfrac{\delta - p_2}{h_b - p_2}, & \delta < h_b \\ F_{bot}, & \delta \ge h_b \end{cases} \tag{8.5}$$

with $p_2 = p_c + p_s$, to which a damper $c_b\dot{\delta}\min(1, \delta/\delta_r)$ is added. Once a button bottoms out at $h_b = 4$ mm the tool's front reaches the face behind it and the wall block pushes through Equation (8.4). A button clicks when its travel passes $p_c = 1.5$ mm and re-arms below 0.5 mm, and it lights only in the order 1 to 4, a press out of order starting the sequence again.

Friction acts on the two wall blocks as an elastic bristle along the contact's tangent $\mathbf{t}_i = (-n_{iy}, n_{ix})$, as shown in Equation (8.6).

$$\begin{aligned} &\dot{z}_k = v_{t,k}, \qquad F_{t,k} = -\,\mathrm{clip}\left(K_t z_k + C_t v_{t,k},\ \pm\mu F_{n,k}\right) \\ &z_k \leftarrow \mathrm{clip}\left(z_k,\ \pm\mu F_{n,k}/K_t\right) \quad \text{after each step} \end{aligned} \tag{8.6}$$

where $k \in \{L, R\}$, $v_{t,k}$ is the tool's speed along $\mathbf{t}_k$, and z_k is set to zero whenever its block is out of contact. The buttons and the slot bottom are smooth. The force on the tool is the sum $-\mathbf{F}_e = \sum_i (F_{n,i}\mathbf{n}_i + F_{t,i}\mathbf{t}_i)$. The peg is seated when it is inside the slot within 0.8 mm of the bottom.

8.3.3 The Channel and the Ledger

Each side knows the other only through two links, one each way, built on the framework's shared delay line, `shared/src/framework/core/channel.js`, with its wandering-jitter option on. The same module carries the radio of the vehicle platoon of Volume 7, Chapter 14. Every 1 ms each side sends one packet, which arrives as given by Equation (8.7).

$$t_{arr} = t_k + \tfrac{T}{2}(1 - j) + T\, j\, \omega(t_k) \tag{8.7}$$

where t_k is the time it was sent, T the round trip, j the jitter share and $\omega \in [0, 1]$ a wandering level that ramps linearly, over each interval of $\tau_j = 0.5$ s, to a new value drawn uniformly at the start of the interval, so that the one-way delay wanders within $\pm j$ of $T/2$ as packets behind one queue do. A packet is lost with probability p, independently, and every packet of a burst is lost. Each packet draws two uniform numbers from its link's own generator, whatever the settings, and each link is seeded from the case's seed and its own index, so the losses of one link cannot depend on anything else. A packet that arrives after a newer one is thrown away, so what a receiver holds never goes back in time, and through a gap it keeps the last packet it had. At reset both links are filled as if they had been up with both devices at rest.

The ledger books the power that enters the channel at each port, as shown in Equation (8.8).

$$\begin{aligned} P_m &= -\mathbf{F}_{mh} \cdot \dot{\mathbf{x}}_m, \qquad P_s = -\mathbf{F}_p \cdot \mathbf{v}_{cmd} \\ E_{created}(t) &= -\int_0^t (P_m + P_s)\, \mathrm{d}t \end{aligned} \tag{8.8}$$

where $\mathbf{v}_{cmd}$ is the velocity the channel asks of the slave and $\mathbf{F}_p$ the force the architecture reports at the slave's port, the measured $\mathbf{F}_e$ for position–force and the drive force $\mathbf{F}_s$ otherwise. With no delay and a reflection gain of one, position–force hands the slave the master's velocity and the master the slave's force within one period, so the two terms cancel but for that period. A negative $E_{created}$ is energy in flight, and a positive one is energy the channel has put out that neither port put in.

🕮 **Pause.** Try Exercise 8.1 before reading on.

8.3.4 The Scripted Operator

In AUTO the hand's aim follows a script that reacts only to what an operator can perceive, the force the hand pushes with, filtered over 50 ms as $\bar{F}_h$, and the video of the slave, the lamps and the peg, which arrives with the slave's packets one delay late. A task is a list of steps. The hand moves its aim at 60 mm/s in free space, 30 mm/s over the last 15 mm before an expected surface and 15 mm/s while pressing. It takes a felt force above 0.6 N for contact only once the video shows the slave stopped short of the aim, except under model mediation, where the force is rendered locally and is trusted at once, and it takes one above 4 N for contact whatever the video shows. A step that ends on something perceived ends 0.2 s later, and the hand meanwhile keeps doing what it was doing, except that it stops advancing at once at a felt 8 N. After a rest of 1 s the wall task presses three times at $x = -140$ mm until $\bar{F}_h$ reaches 3 N under the same rule, holds each press 1.5 s, and backs off to 30 mm in front of the face with 0.5 s of rest between presses. A button is pressed until the video shows its lamp, a felt click (a drop of 0.5 N after 1.4 N) or the 8 N cap, and pressed again up to twice if the lamp stays dark a round trip and a second later. The contour is traced from 10 mm before x_0 to 10 mm past x_1 at 20 mm/s, aiming 3 mm past the drawn face. The peg is lined up 3.5 mm off the slot's center and pushed in, and once the video shows it stalled for 1 s while the hand feels more than 1 N, the aim moves across at 3 mm/s, by at most 8 mm, toward the slot as seen. Under the move-and-wait strategy

Table 8.2 Constants of the Model. V Is Adjustable in the Show Model Dialog, H Is Kept Out of It and C Is Fixed in the Source

Symbol	Meaning	Value	Class
Devices			
m_m, b_m	master mass, damping	0.5 kg, 20 N s/m	V
$F_{m,max}$	master force limit, an axis	20 N	V
m_s, b_s	slave mass, damping	2.0 kg, 5 N s/m	V
Site			
K_e, B_e	wall stiffness, damping	5000 N/m, 80 N s/m	V
μ	friction on the wall blocks	0.4	V
δ_r	damping fade-in	0.5 mm	C
K_t, C_t	bristle stiffness, damping	5000 N/m, 60 N s/m	C
R_T	tool radius	5 mm	C
y_w, A	face, contour depth	150, 12 mm	C
x_0, x_1	contour ends	−120, −40 mm	C
—	buttons, centers	−10, 20, 50, 80 mm	C
—	buttons, width by height	18 by 4 mm	C
F_{break}	button break force	2.0 N	H
p_c, p_s, h_b	click, snap, travel	1.5, 0.3, 4 mm	C
F_{low}, F_{bot}, c_b	after the snap, bottom, damping	0.8, 1.2 N, 4 N s/m	C
—	slot center	128 mm	C
w_s, d_s, c_s	slot width, depth, chamfer	12, 30, 2 mm	C
—	clearance a side	1 mm	H
Channel			
τ_j	period of the wandering delay	0.5 s	C
—	burst, satellite hop	1 s, +500 ms	C
—	packets in flight a link	4096	C

the aim moves one increment at 30 mm/s, 10 mm in free space and 2 mm near or in contact, then holds until the video shows the slave within 1.5 mm of it, or a round trip and a half and 0.3 s have passed, and then takes the reaction time. In MANUAL the two aim sliders, moved by the arrow keys, are the student's hand. The operator's stiffness K_h and damping B_h are illustrative values, which the application attributes to the haptics literature.

8.3.5 Counting an Oscillation

The scorecard counts a force reversal each time the contact force turns from rising to falling or back by at least 1.5 N, ignoring a turn within 60 ms of the last and the first turn after the hand starts to back off. A contact episode lasts through bounces while the hand still aims past the slave and ends 50 ms after contact is lost with the hand no longer pushing, and the status reads CONTACT OSCILLATION once an episode holds four reversals. A click starts the episode's count again, and the reversals of the following 0.3 s belong to the snap. An active flag also clears after 1 s without a qualifying reversal, even if the hand keeps aiming past the slave. These are teaching thresholds.

8.3.6 Start, Step and Seed

Every case begins at rest, with the hand's aim, the master and the slave together at the task's starting point, at $y = 100$ mm and so 50 mm short of the face, and both bristles relaxed. The engine is the one of Section 1.6.1. A classical Runge-Kutta step of fourth order and 1 ms integrates the ten states, the two controllers act once a millisecond, and the historian records at 50 Hz, with a 1 kHz scope of the contact force and the ledger beside it. Seeded with 20261001, a case replays bit for bit. With the physics step halved and the control period kept at 1 ms, the press force with no delay and the energy created over the first contact at 100 ms move by a relative 6.4×10^{-6}. All 39 of the application's checks and its 11 checks of the scenario completion rules pass.

8.3.7 Assumptions

Two decoupled axes and a disc. Each device moves in x and y without rotation, so the peg is a disc seen end-on. It can stick by friction but cannot wedge as a real peg does, and the slot task is a

Table 8.3 Controller and Operator Settings, Defaults and Ranges

Symbol	Setting	Default	Range
—	architecture	position–force	4 kinds
k_f	reflection gain	1	0–1.5
K_p	slave stiffness, N/m	2000	100–5000
K_d	slave damping, N·s/m	80	0–200
$F_{s,max}$, F_{lat}	slave force limits, N	50, 50	5–80, 1–50
b	wave impedance, N·s/m	50	5–500
—	lost or late waves	held	or rebuilt
—	passivity controller	off	on
α_{max}	master damper limit, N·s/m	500	0–1000
β_{max}	slave damper limit, mm/s per N	100	0–200
f_u	model update rate, Hz	10	1–50
$\hat{K}_0$	wall stiffness prior, N/m	5000	500–20000
K_h, B_h	hand, N/m and N·s/m	300, 10	to 2000, 60
—	strategy	continuous	move and wait
—	task	three presses	5 tasks

sideways contact rather than a jam.

One frame at one scale. A real master is usually smaller than its slave and its motions are scaled, which multiplies the two ports' powers by different factors and moves every gain limit. A surgical console that scales and filters the surgeon's motion is treated in Volume 20, Chapter 14.

A linear hand on a script. The operator is a spring and a damper of fixed values about a scripted aim, with a fixed reaction time. Real operators stiffen their grip, slow down and adapt to a delay, and the grip alone moves the limits of Section 8.5.

Damped devices. The master carries 20 N s/m of damping and the wall 80 N s/m. With a bare master of 2 N s/m against a wall of 20 N s/m, the loop of Section 8.5 with no delay is stable only below a reflection gain of 0.43, and the running model keeps still at 0.45 and oscillates at 0.5, so these values are what makes full reflection workable at all.

Ideal sensors. Each device measures its own position and velocity exactly, and the slave's force sensor reads the contact force without noise, lag or quantization, so every delay in the loop belongs to the channel and the holds.

A clean channel. Packets are delayed by a wandering amount, lost and dropped in bursts but never corrupted or duplicated, the two ends share a clock, and bandwidth, queueing that depends on the traffic and the compression of the video are not modeled.

Illustrative numbers. The dimensions, stiffnesses and thresholds are values the application chose for teaching, not data from a particular teleoperator.

8.4 The Controllers, Period by Period

Within each millisecond the two sides take turns. The master takes the newest packet from the slave, computes $\mathbf{F}_{mh}$ by the architecture in force, applies the passivity damper if it is on and the motors' limit, and sends its packet. The slave then takes the newest packet from the master, which with no delay is the one just sent, computes its command and its drive force, applies its own damper and limits, and sends its packet, which the master reads on the next period. With no delay the shortest round trip is therefore one period of transport plus the two holds. The ledger books the period's power, and last the operator moves the aim. The settings are listed in Table 8.3.

8.4.1 Position–Force and Position–Position

Position–force sends the master's position and velocity forward and the slave's measured contact force back, as shown in Equation (8.9).

$$\begin{aligned} \mathbf{F}_s &= \mathrm{sat}\left(K_p(\mathbf{x}_{cmd} - \mathbf{x}_s) + K_d(\mathbf{v}_{cmd} - \dot{\mathbf{x}}_s)\right) \\ \mathbf{F}_{mh} &= -k_f\,\tilde{\mathbf{F}}_e \end{aligned} \tag{8.9}$$

where $\mathbf{x}_{cmd}$ and $\mathbf{v}_{cmd}$ are the master's delayed position and velocity, $\tilde{\mathbf{F}}_e$ the slave's delayed force, and the saturation limits the drive to $F_{s,max}$ toward the wall and to $\min(F_{lat}, F_{s,max})$ across it, both scaled by the drive capacity. Position–position runs the same slave and returns the slave's position instead, so the master pulls the handle toward where the slave was, $\mathbf{F}_{mh} = k_f[K_p(\tilde{\mathbf{x}}_s - \mathbf{x}_m) + K_d(\tilde{\dot{\mathbf{x}}}_s - \dot{\mathbf{x}}_m)]$, and the slave's port force is $\mathbf{F}_s$. In both, the force on the handle is clipped to $\pm F_{m,max}$ per axis after any damper.

8.4.2 Wave Variables

The wave architecture sends the forward wave u and returns w, with the wave impedance b, as shown in Equation (8.10).

$$\begin{aligned} \mathbf{F}_{mh} &= \sqrt{2b}\,\tilde{\mathbf{w}} - b\,\dot{\mathbf{x}}_m, \qquad & \mathbf{u} &= \frac{b\,\dot{\mathbf{x}}_m - \mathbf{F}_{mh}}{\sqrt{2b}} \\ b\,\mathbf{v}_{sd} &= \sqrt{2b}\,\tilde{\mathbf{u}} - \mathbf{F}_s, \qquad & \mathbf{w} &= \frac{b\,\mathbf{v}_{sd} - \mathbf{F}_s}{\sqrt{2b}} \end{aligned} \tag{8.10}$$

where the slave's command $\mathbf{x}_{sd}$ integrates $\mathbf{v}_{sd}$. The slave solves its PD, $\mathbf{F}_s = K_p(\mathbf{x}_{sd} + \mathbf{v}_{sd}\Delta t - \mathbf{x}_s) + K_d(\mathbf{v}_{sd} - \dot{\mathbf{x}}_s)$, together with the wave equation in closed form within the period Δt, and a force over its limit is clipped with $\mathbf{v}_{sd}$ recomputed from the clipped force. At each end the power entering the network is then half the square of the wave sent less half the square of the wave received, so a channel that only delays the waves holds the wave energy in flight. A receiver either holds the last wave through a gap or reconstructs it, scaling the wave it uses by Equation (8.11).

$$\kappa = \min\left(1,\ \sqrt{\frac{\max(0,\ \tilde{E}_w - E_{used})}{\frac{1}{2}\,\tilde{w}^2\,\Delta t}}\right) \tag{8.11}$$

where $\tilde{E}_w$ is the sender's cumulative wave energy carried by the newest packet and E_{used} what this receiver has spent, so a lost packet's energy is spent later but never twice.

8.4.3 The Time-Domain Passivity Controller

Over position–force, position–position or wave variables, each port keeps the energy that has entered the network through it, E_{in}, apart from the energy that has left, E_{out}, and sends E_{in} with every packet. A port may put out only what the other side has put in, as far as the channel has told it, and a variable damper takes the excess, as shown in Equation (8.12).

$$\begin{aligned} \varepsilon &= -P_0\,\Delta t - \max\left(0,\ \tilde{E}_{in}^{other} - E_{out}\right), \qquad & P_0 < 0 \\ \alpha &= \min\left(\alpha_{max},\ \frac{\varepsilon}{\Delta t\,|\dot{\mathbf{x}}_m|^2}\right), \qquad & \mathbf{F}_{mh} \leftarrow \mathbf{F}_{mh} - \alpha\,\dot{\mathbf{x}}_m \\ \beta &= \min\left(\beta_{max},\ \frac{\varepsilon}{\Delta t\,|\mathbf{F}_p|^2}\right), \qquad & \mathbf{v}_{cmd} \leftarrow \mathbf{v}_{cmd} - \beta\,\mathbf{F}_p \end{aligned} \tag{8.12}$$

where P_0 is the port's power before its damper and each damper is zero unless $\varepsilon > 0$. The master's damper is a damping on the handle, and the slave's an admittance that backs the command off along the port force. For position–force and position–position that change of velocity also moves the commanded position, and the drift it leaves is walked back at 20 mm/s while the slave's damper is idle and the walk puts no energy out at the port, or puts out only what is in hand. A clipped damper lets the rest through, and the ledger shows it.

8.4.4 Model Mediation

Under model mediation the master renders a model instead of the slave's force. It steps a local copy of the slave, with the same mass, damping, PD and limits, four times per period against the site's drawing shifted by an estimated offset $\hat{\Delta}$ with stiffness $\hat{K}$ and damping B_e, without friction, and renders $\mathbf{F}_{mh} = -k_f\mathbf{F}_{copy}$, the copy's PD force. Like the Smith predictor of Section 1.4.3, the master

closes its fast loop on an undelayed model and leaves the delayed measurements to correct the model. The slave tracks the delayed master as in position–force and fits the site from its own contacts by recursive least squares, as shown in Equation (8.13).

$$\begin{aligned} \delta_{prior} &= F_n/K - \Delta n_y = \varphi^{\mathsf{T}}\theta \\ \varphi &= [F_n,\ -n_y]^{\mathsf{T}}, \qquad \theta = [1/K,\ \Delta]^{\mathsf{T}} \end{aligned} \tag{8.13}$$

where δ_{prior} is the tool's penetration into the drawing, F_n the measured normal force and n_y the drawing's normal. A sample is taken only while the tool presses one rigid body, no button, above 0.5 N and slower than 5 mm/s along the normal. The update forgets with $\lambda = 0.9995$, starts from the prior $\hat{K}_0$ and zero offset with uncertainties of 50 % on $1/K$ and 20 mm on Δ against 0.2 mm of misfit per sample, keeps $1/K$ between $1/50\,000$ and $1/500$, and is published at f_u. The master moves $\hat{\Delta}$ toward each new estimate at no more than 10 mm/s and $\hat{K}$ with a 0.2 s lag, so a correction never kicks the hand.

8.4.5 Limits, Signs and the Models Kept Apart

No loop of this application uses the velocity-form PID of Section 1.6.2. The slave's PD and the master's laws are written out inline with no integral term, which leaves nothing to wind up and no need for anti-windup, and none of the forces is rate-limited. The derivative terms take the velocities as measured, the slave's own and the master's as carried by its packet, with no differencing and no filter. Clips, applied after the dampers, are the only output limits. The application's own sign checks confirm that the slave pushes toward a command ahead of it on each axis, that position–force pushes the handle back from a slave pressing into the wall and that a forward wave moves the slave forward. The four-channel architecture was left out, because it gives the ledger no single pair of force and velocity at each port.

The model of Section 8.3 is not one that any controller holds. The passivity controller keeps only energy books, and under model mediation the master keeps a copy of the slave against its estimated site. The linearization of Section 8.5 is a third model, built for analysis, which the application never runs.

8.5 The Gain Limit of Force Reflection

Pressing a flat part of the face along y, with the contact's damping fully faded in and the aim held, position–force is a linear loop. The delay sits inside a loop closed through the operator's hand, and, as in Section 1.4.2, it caps what the loop may do. In continuous time, with an effective delay T_e, its loop gain is Equation (8.14).

$$\begin{aligned} L(s) &= \frac{k_f\,(K_e + B_e s)(K_p + K_d s)\,\mathrm{e}^{-sT_e}}{D_m(s)\,D_s(s)} \\ D_m(s) &= m_m s^2 + (b_m + B_h)s + K_h \\ D_s(s) &= m_s s^2 + (b_s + K_d + B_e)s + K_p + K_e \end{aligned} \tag{8.14}$$

where D_m is the master under the hand and D_s the slave pressing the wall. At zero frequency $L(0) = k_f K_{ser}/K_h$, where $K_{ser} = K_p K_e/(K_p + K_e) = 1429\,\mathrm{N/m}$ is the slave's PD and the wall in series. Through a long delay the phase of $\mathrm{e}^{-j\omega T_e}$ passes $-\pi$ at frequencies only $2\pi/T_e$ apart, so the loop is stable at every long delay only if $|L(j\omega)| < 1$ at all frequencies. For the 300 N/m hand, whose master and grip are overdamped, the largest $|L|$ is at zero frequency, which gives the bound of Equation (8.15).

$$k_f < \frac{K_h}{K_{ser}} = \frac{300}{1429} = 0.21 \tag{8.15}$$

Through a long delay a wall can be rendered no stiffer than the hand that holds it.

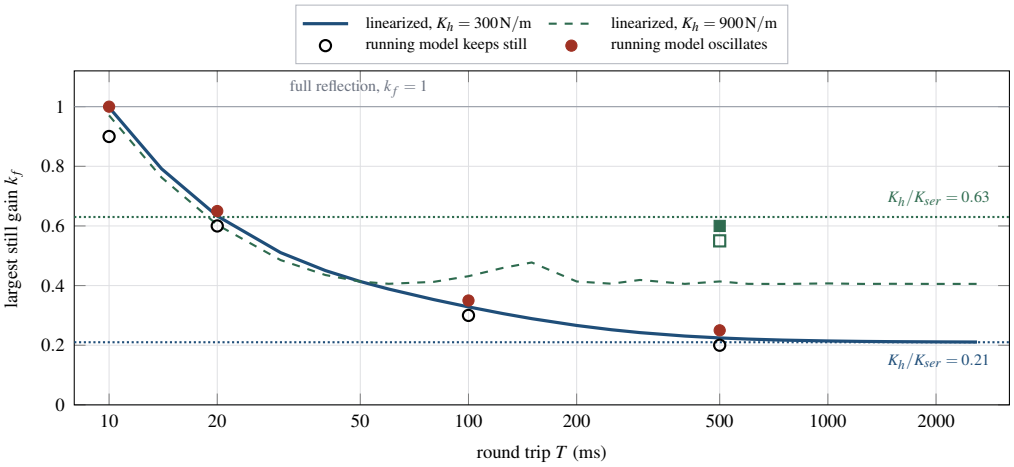


Figure 8.2 The largest reflection gain at which position–force keeps a press still, against the round trip. The curves are the sampled loop linearized in contact for the 300 N/m hand (solid) and for a 900 N/m grip with the same damping (dashed), and the dotted lines their static bounds K_h/K_{ser}. The marks are the running model's verdicts on the three presses of the wall task at each round trip, kept still (open) or flagged as an oscillation (filled), circles for the 300 N/m hand and squares for the firmer grip.

The numbers in this section come from the loop as the application samples it rather than from Equation (8.14). Both plants are discretized exactly over the 1 ms period with the forces held, the slave's PD acts on its own sampled state, the master reads the force N_b periods late and the slave reads the master N_f periods late, with $N_f = N_b = T/(2\Delta t)$, and $N_f = 0$ and $N_b = 1$ with no delay. For each T the largest stable k_f is the gain margin at the frequencies where the delayed loop's phase is $-\pi$. Equation (8.14) agrees with it within 0.5 % at every round trip when T_e is the round trip plus 1 ms for the two half-period holds, and 2 ms with no delay, where the master reads the slave one period late.

The limit falls fast and then levels, as shown in Figure 8.2. It is 1.00 at a round trip of 10 ms, 0.633 at 20 ms, 0.329 at 100 ms, 0.252 at 250 ms, 0.2245 at 500 ms and 0.211 at 2.6 s, approaching the bound of Equation (8.15) from above. Where the instability grows quickly the running model agrees, still at 0.9 and oscillating at 1.0 for 10 ms, still at 0.60 and oscillating at 0.65 for 20 ms, and still at 0.30 and oscillating at 0.35 for 100 ms. At 500 ms it keeps still at 0.20 and oscillates at 0.25, the settings of the slider's 0.05 grid on either side of the limit. Full reflection, the transparent setting, therefore needs a round trip under about 10 ms.

With no delay the limit depends on the press. The 2 ms of sampling leave a limit of 4.51 when the wall's damping is fully engaged, 0.58 with none, and 2.53 with the 61 % of it that a press of 1.53 N engages. A 3.06 N felt press at gain k_f pushes the peg with $3.06/k_f$, so the limit solves itself at 2.20. The running model, given gains beyond the slider's maximum of 1.5 in a counterfactual run, keeps still at 2.0 and oscillates at 2.5. An earlier linearization that left the wall's damping out of the reflected force gave 1.28 here.

Near the boundary the instability is slow, and a verdict from three presses can miss it. At 500 ms the dominant root of the sampled loop, the root of its characteristic equation with the largest modulus, grows by a factor of 14.7 a second at full reflection, with a period of 1.11 s, but at 0.248, past the limit, only by 1.20 a second, while at 0.22 it decays by 3.5 % a second. The firmer grip shows the same effect more strongly. At 900 N/m with 10 N s/m the master follows the hand's force nearly undiminished up to about 40 rad/s, where the slave's reflected force has grown, so $|L|$ peaks near 36 rad/s at 1.55 times its static value and the limit levels at 0.41 rather than at the static 0.63, yet the running model keeps still up to 0.55, where the oscillation grows by only 1.69 a second, and is

Table 8.4 The Nine Cases and the Challenge

#	Change from the reference line	Teaching point
1	none, three presses with no delay	the wall is felt
2	$T = 100\,\text{ms}$	the contact chatters
3	$T = 500\,\text{ms}$	no gain is still and transparent
4	$T = 500\,\text{ms}$, wave variables	passive, and mud
5	$T = 500\,\text{ms}$, passivity controller	a damper that waits
6	as 4, $j = 20\,\%$, $p = 10\,\%$, burst at 4.9 s	a held wave keeps pressing
7	$T = 1\,\text{s}$, model mediation, $\Delta = -8\,\text{mm}$	right until it is not
8	peg, $T = 250\,\text{ms}$	a sideways contact
9	buttons, $T = 2.6\,\text{s}$, $k_f = 0$, move and wait	safe and slow
C	buttons then peg, $T = 400\,\text{ms}$, $p = 5\,\%$	choose an architecture

Table 8.5 Measured Results of Each Case and Variant

Case and configuration	Result
1, as shipped	3.06 N at the wall for 3.06 N felt, 1243 N/m felt, ledger at most 0.78 mJ
1, contour	rms 0.15 mm, in contact throughout
2, as shipped	41 reversals, 25.7 N, 15.5 J, flagged at 2.76 s
2, k_f 0.35 / 0.30	oscillates / still, 10.8 N, 110 mJ
2, position–position	still, 3.8 N, 6.45 N of drag
3, as shipped	master thrown back 94.6 mm, 9.54 J
3, k_f 0.20 / 0.10	still, 23.7 / 27.8 N for 3.75 / 2.50 N felt
3, $K_h = 900\,\text{N/m}$	still to 0.55, flagged at 0.60
4, b = 20, 50, 200	walls of 76, 173 and 1758 N/m, drag 2.28, 3.53 and 6.24 N
5, as shipped	dampers on 14.5 % and 17.2 % of 40 s, 2.95 mJ created
5, $\alpha_{max} = 50\,\text{N s/m}$	274 mJ created, 1.7 s of oscillation
6, held / rebuilt waves	7.16 mJ created, peg 30.4 mm ahead / never positive
7, as shipped	first press 13.78 N for 4.79 N felt, third 3.15 for 3.05 N
7, $\Delta = 0$ / $+4$ mm	every press 3.14 N / the wall never reached
8, as shipped	master across 62 to 187 mm, 93 N on the slot walls, 225 J
8, passivity controller	seated at 3.745 s, 1.1 N on the walls
9, move and wait	272.9 s, 21.8 N
9, model mediation, continuous	17.3 s, 4.36 N
C, as shipped	41 reversals, 108.8 N at the pause
C, model mediation	12 reversals, 4.08 N, done at 18.7 s

flagged at 0.60. At long delays the reverse happens. With full reflection at 1 s the instability is a slow bounce, of period 2.12 s in the linearized loop. On the running model the wall is struck six times, every 2.3 to 2.8 s, with too few reversals in any one press to fill an episode, so the flag never rises while the strikes reach 40.6 N and the channel creates 9.62 J. The ledger, not the reversal count, is the signal that does not miss.

A reduced gain does not make the channel passive either. With no delay, a gain of 0.5 lets the slave do work on the wall of which the hand pays only half, and the ledger books 12.2 mJ over three presses against 0.78 mJ at a gain of one, while a gain of 1.5 returns more on the release than it took on the press and books 7.7 mJ. A passive channel is sufficient for a still contact but not necessary, because the hand, the devices and the wall dissipate what the channel creates.

🕮 **Pause.** Try Exercise 8.2 before reading on.

8.6 Nine Cases and a Challenge

The cases of Table 8.4 are variations on the settings of Tables 8.2 and 8.3, each changing only what its row names. Every figure in this section was measured headlessly, the engine running without its interface at the default seed, in simulated time, on the scenarios of Section 1.6.4, and Table 8.5 collects them.

8.6.1 No Delay, Then a Tenth of a Second

In case 1 the scripted operator presses the wall three times with full reflection and no delay, until the hand feels 3 N. Each press holds 3.06 N at the wall for 3.06 N on the handle, and the master stops 2.06 mm after the felt force first passes 0.5 N, a felt wall of 1243 N/m against the 1429 N/m of the series springs. The presses are done at 13.4 s with a peak of 3.15 N, the ledger never exceeds 0.78 mJ, and the contour, traced at no delay, keeps an rms gap of 0.15 mm in contact the whole way.

Case 2 adds 50 ms each way. The peg first touches at 2.12 s and pushes to 5.99 N, the force reaches the hand 50 ms after it rose, when the hand has already pushed on, and the delayed force throws the master back. The peg leaves the wall at 2.28 s, when the channel has created 34.1 mJ, and strikes again at 2.43 and 2.76 s, with 42.1 mJ and 593 mJ created, the second of which the detector first flags. The ledger turned positive two touches before the status did. Over the run the channel creates 15.5 J, with 41 reversals, a peak of 25.7 N and 6.5 s of oscillation, all of it dissipated by the hand, the devices and the wall, and Figure 8.3 shows the contact during the third press. A gain of 0.35 still oscillates, while 0.30 keeps still with the peg pressing up to 10.8 N, less than a third of it felt, and the channel still creating 110 mJ. Position–position does not chatter (3.8 N at most) but drags the handle toward where the slave was, up to 6.45 N on the way to the wall against 1.19 N under position–force, and the contour traced at 100 ms under position–force bounces along the bump in contact only 40.5 % of the way.

> **TRY IT IN THE APP** **2 · 100 ms of Round Trip**
>
> Load the case and press Run on the Channel view. Watch the energy ledger as the peg first touches the wall at 2.12 s: by the end of that touch the channel has created 34.1 mJ. The status line first reads Contact oscillation during the third touch, at 2.76 s. The ledger turned positive two touches before the status did.

8.6.2 Half a Second With No Cure

Case 3 is the honest infeasible case of position–force. At full reflection the first touch, at 2.62 s, throws the master back 94.6 mm, from 160.1 to 65.5 mm, and the run creates 9.54 J with 2.97 s of oscillation. Every gain tested from 0.25 to 1 oscillates. At 0.20, the slider's next step down, the contact keeps still, but holding 3.75 N on the handle drives the peg into the wall at 23.7 N, a ratio of 6.3, and at 0.10, 2.50 N on the handle is 27.8 N at the wall. A firmer grip moves the limit, to 0.55 at 900 N/m on the running model, although not to its static bound, for the reason of Section 8.5. No choice of gain is both still and transparent at this delay.

8.6.3 Three Passive Cures at Half a Second

Case 4 sends waves with $b = 50\,\mathrm{N\,s/m}$. The ledger never turns positive and holds up to 37.9 mJ in flight, and the contact keeps still, but the master travels 14.4 mm while the felt force rises from 0.5 to 2.99 N, a wall of 173 N/m. The impedance sets the trade. At $b = 20$ the handle drags at most 2.28 N in free space and the wall is 76 N/m. At $b = 200$ free space drags 6.24 N and the wall is 1758 N/m, firmer than with no delay, but the contact bounces for 0.84 s as the waves reflect between the ends. With the task changed to the contour, the trace at 500 ms keeps contact 79.1 % of the way with an rms gap of 1.12 mm.

> **TRY IT IN THE APP** **4 · Wave Variables at 500 ms**
>
> Press Run and watch the ledger, which never turns positive. On the Cell view the master travels 14.4 mm into the wall while the felt force rises from 0.5 to 2.99 N. Press Reset and run with the Wave impedance at 20, then at 200: the rendered wall is 76 N/m, then 1758 N/m, and at 200 the handle drags 6.24 N in free space.

Case 5 returns to position–force at 500 ms with the passivity controller. Over the case's 40 s the master's damper acts during 14.5 % of the time and the slave's during 17.2 %. The slave's acts only

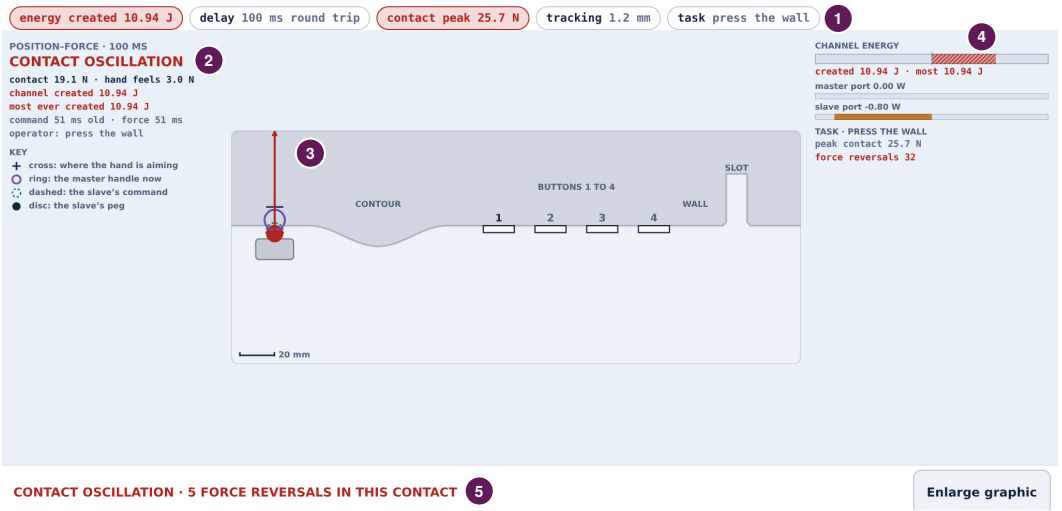


Figure 8.3 Case 2, 100 ms of round trip, at $t = 11.00\,\mathrm{s}$ (the clock is cut) in the Cell view with no control changed, cropped to the plant panel. The peg strikes the wall during the third press with 19.1 N, drawn as the arrow at the peg, while the force reaching the master left the slave 51 ms earlier, before this strike. (1) The badge row: energy created, the round trip and the contact peak. (2) The left column gives the contact force beside the 3.0 N the operator perceives over 50 ms, 10.94 J created by the channel, and newest packets 51 ms old. (3) The peg, the master's ring and the arrow of the contact force at the wall. (4) The channel-energy and task panels count 32 reversals, a peak of 25.7 N and 10.94 J created at most. (5) The status reads Contact oscillation, 5 force reversals in this contact.

while the peg touches the wall, which it does for 29.0 % of the time, and the master's only while a contact force is reaching the handle, up to the 250 ms of the return link after a touch ends, so neither acts in free space. The contact keeps still with a peak of 6.84 N, and the channel creates at most 2.95 mJ against 9.54 J without the controller, while the dampers take 634 mJ. The price is position and feel. The slave's damper lets its command fall up to 18.3 mm behind the master, and the hand travels 10.9 mm into a wall of about 236 N/m, because the slave may not do work the operator has not yet paid for and the payment arrives a round trip late. Limited to $\alpha_{max} = 50\,\mathrm{N\,s/m}$, the master's damper runs out, the channel creates 274 mJ and the contact oscillates for 1.7 s.

Case 6 runs wave variables on a channel whose delay wanders by 20 % and which loses one packet in ten, and both links drop out for 1 s at 4.9 s as the hand backs off from the first press. Holding the last wave, the slave keeps pressing the wall at 2.68 to 2.77 N through the whole second while the master backs off 42.5 mm, and at 13.5 s it still presses at 2.59 N, 30.4 mm ahead of the master, having been off the wall for 0.14 s in all since the dropout. The ledger turns positive, 7.16 mJ, and the second press raises the oscillation flag for 1.39 s. With the dropout removed from the script, a counterfactual run, the jitter and loss alone create 1.15 mJ, and with the jitter and loss set to zero the dropout alone creates 1.71 mJ. With reconstruction by Equation (8.11) the slave lets go at 5.315 s, before the link returns, and the ledger never turns positive. Both lose position, because waves carry velocity and lost velocity is never made up, and with reconstruction the peg is still 11.9 mm ahead of the master at 10 s. These figures belong to the default seed, and the losses move them. On five other seeds the hand is still holding the first press when the link drops on three, whose slaves let go 0.3 to 0.4 s after it returns, and the held waves peak at 0 to 14.1 mJ created, against 0 to 8.1 mJ from the jitter and loss alone, so the split between the two causes lies within the spread. On every seed reconstruction lets go between 5.26 and 5.34 s and never lets the ledger turn positive.

8.6.4 A Model of the Wall at a Full Second

Case 7 has a round trip of 1 s and the real wall 8 mm closer than the drawing the model starts from. On the first press the peg meets the wall early, while the hand still feels nothing, and presses it at 13.78 N while the hand feels at most 4.79 N, and the ledger books 84.4 mJ that the master never put in. The slave's estimate is within 0.5 mm of the truth 28 ms after the touch, and the master's model gets there 1.33 s after it, half a second for the news and the rest for the rate limit. The second press peaks at 4.80 N and the third at 3.15 N for 3.05 N on the handle. With the wall where the drawing says, every press is 3.14 N, with it 4 mm short the presses are 8.86, 4.08 and 3.15 N, and with it 4 mm beyond, the hand presses the model's wall and the peg never reaches the real one. A prior of half the true stiffness costs only the first press, at 4.00 N, and a wall three times stiffer than the prior is estimated at 15 057 N/m.

Pause. Try Exercise 8.3 before reading on.

8.6.5 The Slot, the Moon and the Challenge

Case 8 lines the peg up 3.5 mm off the slot's center and pushes it in with full reflection through 250 ms. The chamfer turns the push sideways, the slot walls push back, and the sideways axis goes unstable as the wall did in case 2. The master swings between 62 and 187 mm across a slot at 128 mm, the peg hammers the slot walls at up to 93 N, the channel creates 225 J, and the peg seats anyway at 3.53 s, by force. A 2 N lateral limit only bounds the swing, to 118 to 138 mm with 28 N on the walls. With the passivity controller the peg seats at 3.745 s with 1.1 N on the walls, as it does with wave variables (1.5 N) and with model mediation at 4.46 s (1.1 N). A disc with no rotation could stick only if pushed sideways more than $1/\mu = 2.5$ times as hard as along the slot, so the jam of a real peg does not occur, and the soft hand fed by the chamfer centers the peg instead. A peg that can stick in a chamfered hole under force control is the subject of Volume 20, Chapter 13.

Case 9 presses the four buttons through the 2.6 s of a lunar link with no force feedback, by move and wait. A 10 mm step in free space takes 3.15 s, a 2 mm step near contact 2.86 to 4.47 s, the longest when the slave presses and the video cannot show it arriving, and the 83 steps take 272.9 s with a peak of 21.8 N. Moving continuously with no force feedback takes 15.0 s but presses blind, at up to 24.0 N. Model mediation, moving continuously, takes 17.3 s at 4.36 N, because the hand feels the local model's buttons click at once, and with move and wait it takes 198.8 s at 2.25 N. Wave variables make five presses out of order and never finish, and the passivity controller never presses a button, because the operator's payment arrives 2.6 s late.

> **DID YOU KNOW? Slow and Careful Still Presses Hard**
>
> From the simulator: through the 2.6 s lunar link with no force feedback, move and wait presses the four buttons in 272.9 s with a peak of 21.8 N, while model mediation, moving continuously, takes 17.3 s at 4.36 N (Table 8.5). Only the local model lets the hand feel each click at once.

The challenge asks for the four buttons in order and the peg seated through 400 ms with one packet in twenty lost, with at most 16 force reversals, a peak under 10 N and the task done within 25 s, while the same task with no delay makes 8 reversals. A run counts only if its round trip stays at or above 400 ms and its loss at or above 5 % at every physics step, so that clean run, which meets the other limits, earns nothing. Table 8.6 compares the configurations as the scorecard shows them when the run pauses, 2 s after the task. As shipped, position–force bottoms the first button and presses on to 13.1 N while the hand feels 2.0 N, then throws the handle 43.2 mm back. When the task is done at 16.3 s it has made 30 reversals at up to 73.3 N, and it keeps hammering, so the pause shows 41 reversals and 108.8 N (41 or 42 and 108.8 to 109.9 N on five other seeds), 2.6 and 10.9 times the limits. Wave variables pass one reversal from the limit, and the passivity controller passes with no margin, because at 450 ms, or with the slave's stiffness 20 % lower, it stalls at a button. Model mediation passes inside the limits by 4 reversals, 5.9 N and 6.3 s, and with margin at 450 and 600 ms,

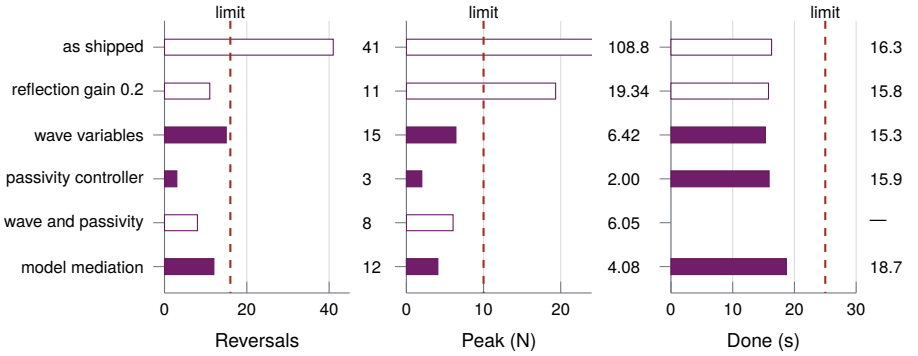


Figure 8.4 The challenge of Table 8.6 as a chart: force reversals against the limit of 16 (left), peak contact force against 10 N (middle) and the time to finish against 25 s (right), as the scorecard shows them when the run pauses. Dark bars belong to configurations that met the target, white bars to those that missed it. The as-shipped peak runs off its axis, and wave variables with the passivity controller never finish. Notice that every configuration that finishes does so within the 25 s, so the reversals and the peak decide the target, and that wave variables pass one reversal from the limit.

Table 8.6 The Challenge as Scored When the Run Pauses

Configuration	Reversals	Peak (N)	Done (s)	Target
as shipped	41	108.8	16.3	missed
reflection gain 0.2	11	19.34	15.8	missed
wave variables	15	6.42	15.3	met
passivity controller	3	2.00	15.9	met
wave and passivity	8	6.05	—	missed
model mediation	12	4.08	18.7	met

at 10 % and 20 % loss, with the slave's stiffness 20 % either way, with 20 % jitter, a 5 Hz update and half the true stiffness as its prior, on three seeds each. It also stays within the limits at 350 ms and with the site 2 mm either way, but the application credits neither run, because the round trip is below its minimum or a disturbance was changed. Figure 8.4 draws the same table against the three limits.

8.7 Technology in Practice

What Measures It

Each side of the teleoperator measures its own position and velocity, and the slave carries a force sensor at its tool, whose reading is what force reflection sends back. The operator also watches the slave on a video that arrives one delay late.

> **TECHNOLOGY** **Sensor: A Strain-Gauge Force Sensor at the Tool**
>
> The force a slave reflects comes from a sensor between its drive and its tool. In a load cell, strain gauges bonded to a metal structure of precisely known elasticity stretch and compress with it, as with a very stiff spring, and a bridge circuit turns their change of resistance into a voltage. Temperature also changes a gauge's resistance, so the bridge cancels it with a dummy gauge that feels the temperature and no strain [20]. Six-axis sensors for force feedback measure three forces and three torques in one compliant body. Strain-gauge designs offer high accuracy but are sensitive to electromagnetic interference and often show cross-axis coupling, in which a load in one direction induces a response in others [21]. The chapter's sensor reads the contact force with no noise, lag or quantization.

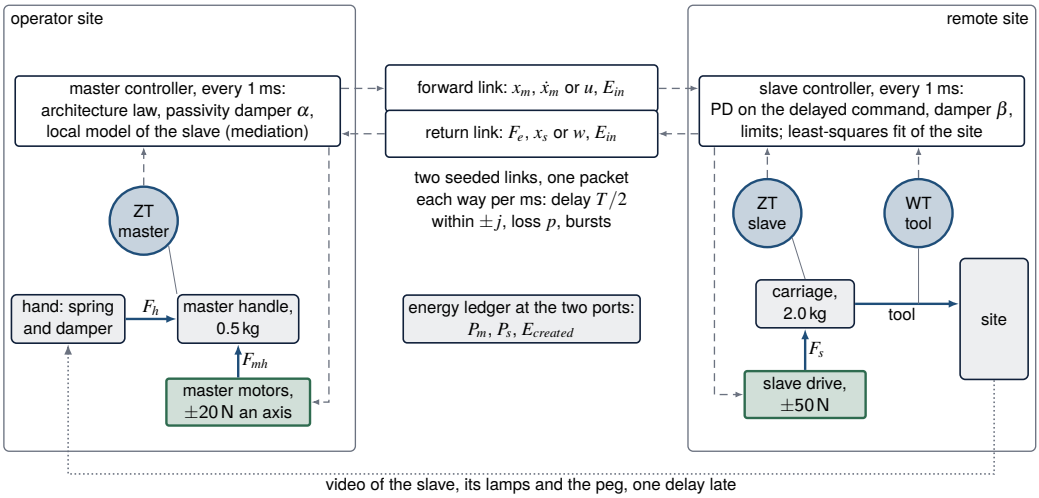


Figure 8.5 The teleoperator of Section 8.3 on its devices. Each side measures its own position and velocity (ZT), the slave reads the contact force at its tool (WT), and the two controllers act once a millisecond on what the seeded links deliver. The ledger books the power at the two ports from the same forces and velocities the controllers exchange, and the dotted path is the video the operator watches, one delay late. Notice that every path from the tool back to the hand passes through the return link or the video, so the hand feels the site only a delay late unless the master's local model renders it.

In the chapter every device measures exactly and the force sensor has no lag, so every delay in the loop belongs to the channel and the holds, as Section 8.3.7 states.

What Moves It

The final elements are the master's motors, limited to 20 N an axis, and the slave's drive, limited to 50 N. The 1989 analysis of force reflection modeled a position-controlled space manipulator as a second-order system, an assumption valid when the arm has no flexible mode in the range of interest, generally below 10 Hz, and took one of 150 lb under a position controller with a bandwidth of 1.5 Hz [18]. The chapter's slave is that kind of model, a 2.0 kg carriage under a PD. On the master side, the same analysis found that the relation between the reflected force and the handle's position is set by the operator and the hand controller, whose characteristics are nonlinear and time varying [18], the part the chapter gives to a linear hand of 300 N/m. Figure 8.5 draws the devices, the two controllers and the links between them.

Where the Controller Runs

Each side runs its own real-time controller, joined to the other only by the network. In the application both controllers act once a millisecond, the physics advances in steps of the same length, and the ledger books each period's power. The layer that holds the chapter's lesson sits between the controllers and the links: the ledger and the passivity dampers act on the forces and velocities the two sides exchange, and under model mediation the master adds a local copy of the slave, stepped four times a period. In a model-mediated teleoperator the slave must also estimate the environment's parameters, which takes time when the environment is complex [22]. The slave of this chapter fits only an offset and a stiffness.

TECHNOLOGY **Platform: The Packet Link Between the Two Sides**

In a conventional bilateral teleoperator, position, velocity and force on both sides are sampled and sent in packets, typically at 1 kHz, for stability and transparency. With the header each packet carries, that rate uses a packet-switched network inefficiently, so perceptual deadband coding sends a sample only when it differs from the last one sent by more than a just noticeable difference, and the receiver fills the gaps, for example by holding the last value [22]. The delay of such a link comes from the signal's time of flight and from queuing and processing at each node, and for a satellite in Earth orbit the node delays dominate [23]. The chapter's links send one packet each way every millisecond and hold the last one through a gap.

What Is Modernizing It

Three developments bear on the delayed channel. The first is model-based, semi-autonomous teleoperation. In studies on satellite servicing, the largest gain came from better situation awareness, through a three-dimensional model of the scene overlaid with the live, delayed video, and from letting operators specify their intended motion precisely, while model-mediated teleoperation reduced the task load without significantly improving task performance [24]. The second is the model of the site itself: for complex geometry, external three-dimensional sensors can capture a precise description of the surface for the master's model [22], where the chapter's model knows only a drawing shifted by one offset. The third is the force sensor. Optical sensors such as fiber Bragg gratings are immune to electromagnetic interference, and capacitive force and torque sensors offer high sensitivity, a simple structure and low power for small tools [21].

IN PRACTICE **Working Through Seconds of Delay**

Ground operators of space robots meet telemetry delays by moving and waiting, and sparse or poorly placed cameras may be an even bigger concern than the delay. In studies on satellite servicing tasks, NASA robot operators kept their keyboard interface, which lets them specify a precise intended motion, over a three-dimensional console, and commanding motion in the frame of the task could improve their performance. The missions put a premium on avoiding failure rather than on time, so the study advises offering several interfaces to choose from at each step of a task [24]. Operators in lunar rover studies estimated that 20 to 100 hours of training would make an operator about 60 % proficient, and full proficiency a yearlong program [4].

8.8 Limitations

The operator is the coarsest part of the model, a linear impedance on a script, where a real operator changes grip and strategy as the delay grows. The devices are point masses in two independent axes, the peg is a disc that cannot wedge, and master and slave move at one scale in one frame. Packets are never corrupted, duplicated or queued behind other traffic, and both ends keep one clock. Model mediation learns a single offset of the whole site along the wall's normal and a single stiffness, so a site that tilts, moves or departs from its drawing in shape is beyond it, and wave variables leave uncorrected the drift that lost waves cause. The four-channel architecture is absent.

OPEN CHALLENGE **Keeping the Local Model True**

A review of model-mediated teleoperation names modeling the environment as its foremost challenge. When the site changes or the estimate is poor, the master's model must be updated quickly, but a sudden change of stiffness or position shows the operator a sudden force, the model-jump effect, which the arm may not stabilize. Fast updates and stability therefore conflict. The approach can be both stable and transparent for relatively simple environments, but existing online estimation cannot make it work efficiently in complex or unknown ones [22]. This chapter's model learns one offset and one stiffness and moves no faster than 10 mm/s.

The oscillation flag counts reversals for teaching. Near the gain limit, and at long delays where the instability is a slow bounce, it can disagree with the linearized loop, and the ledger is then the better witness. All limits, human parameters and challenge thresholds are teaching values, and no figure here describes the performance of a real teleoperator.

OPEN CHALLENGE **Feeling Contact Through a Long Delay**

A predictive display helps an operator position a remote robot through a delay, but it is not feasible once the robot must touch its surroundings, because current models cannot accurately predict what the robot will do next. Bilateral force reflection has been shown impractical and unstable under small to medium delays. Wave variables restore stability, yet delayed force feedback has not proven intuitive to operators, and many researchers have turned to semi-autonomous teleoperation, supervisory or model-based, instead [24]. Progress would be contact feedback, through seconds of delay, that operators find natural and that stays passive on a ledger like this chapter's.

8.9 Conclusion

This chapter has shown a force-reflecting teleoperator, every part of it passive, creating energy in its channel, and has measured that energy at the two ports. With no delay the ledger stays within 0.78 mJ over three presses, while 100 ms of round trip creates 34.1 mJ by the end of the first touch, two touches before the oscillation flag, and 15.5 J over the run. Linearized in contact as it is sampled, the loop tolerates full reflection only below about 10 ms of round trip, and its limit falls toward $K_h/K_{ser} = 0.21$, so that at 500 ms the gain that keeps a press still leaves the peg pressing 6.3 times harder than the hand feels. Wave variables keep the ledger from ever turning positive and render a 173 N/m wall, the passivity controller holds the channel to 2.95 mJ at the cost of a command 18.3 mm behind the master, and model mediation, once its model is right, presses at 3.15 N for 3.05 N felt after a first press of 13.78 N.

Two independent axes, a scripted linear hand and a channel that never corrupts a packet bound what the model can say. A fuller model would add a scaled and rotating master, the four-channel architecture and an operator who adapts to the delay. The simulator is an accessible plant on which the energy books of a delayed interface can be read while it runs.

KEY POINTS

- A teleoperator whose every part is passive can still create energy in its delayed channel, and the ledger shows it two touches before the contact is flagged.
- Through a long delay a wall can be rendered no stiffer than the hand that holds it, and full reflection needs a round trip under about 10 ms.
- A still contact does not prove a passive channel: at 100 ms and a gain of 0.30 the channel creates 110 mJ.
- Each passive cure has a price: a 173 N/m wall with wave variables, a command 18.3 mm behind the master with the passivity controller, and a first press of 13.78 N under model mediation.

Where else this applies. Volume 7, Chapter 14 carries the same delayed, lossy channel, and Volume 2, Chapter 7 regulates a loop whose dead time is a network round trip.

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8.10 Exercises

8.1 Concept check · 2 min

In case 2 the hand, the master, the slave and the wall can each only store or dissipate energy. Yet by the end of the first touch, at 2.28 s, the ledger shows 34.1 mJ created. Where does that energy come from?

(a) From the channel, which pairs the slave's delayed force with a master velocity it never met

(b) From the slave's PD, which stores energy in its stiffness K_p whenever the command runs ahead

(c) From the wall's damping, which fades in over the first 0.5 mm and so returns energy on release

(d) From the hand's spring, which stores energy on each press and returns it when the hand backs off

8.2 Concept check · 1 min

In case 2, at a reflection gain of 0.30, the contact keeps still and no oscillation is flagged, but the ledger shows 110 mJ created. What does this show?

(a) The ledger is in error whenever the oscillation flag stays down, since a still contact proves the channel passive

(b) A passive channel is sufficient for a still contact but not necessary, because the hand, the devices and the wall dissipate what it creates

(c) A gain of 0.30 lies above the linearized limit at 100 ms, so the contact sits on the edge of oscillation

(d) The 110 mJ is the one-period lag of the sampled loop, which the ledger books at every gain

8.3 Concept check · 2 min

Case 7 runs model mediation through a round trip of 1 s with the real wall 8 mm closer than the drawing. On the first press the peg pushes the wall with 13.78 N while the hand feels at most 4.79 N, and on the third press 3.15 N for 3.05 N. Why is the first press so hard?

(a) The least-squares estimator needs several presses to converge, so its offset is wrong until the third press

(b) The master renders the slave's measured force a second late, as position–force does, so the hand learns of the touch late

(c) The master renders its local model of the wall, which stands 8 mm too far, so the peg meets the real wall before the hand feels anything

(d) The 10 mm/s rate limit on the master's model drives the hand's aim into the wall during the first press

8.4 Theory and calculation · 7 min

Use Equations (8.14) and (8.15) with the defaults of Tables 8.2 and 8.3.

(a) Compute K_{ser}, the static bound K_h/K_{ser} for the 300 N/m hand, and the stiffness $k_f K_{ser}$ that the hand feels at a gain of 0.20. *Checkpoint:* 1429 N/m, 0.21 and about 286 N/m, just softer than the hand.

(b) For a grip of 900 N/m the static bound is 0.63, but $|L(j\omega)|$ peaks near 36 rad/s at 1.55 times its static value. Estimate the limit through a long delay. *Checkpoint:* About $0.63/1.55 = 0.41$.

(c) At 500 ms and full reflection the dominant root grows by a factor of 14.7 a second with a period of 1.11 s. At a gain of 0.248 it grows by 1.20 a second. Find the growth over one period in the first case and over one 1.5 s hold of a press in the second. *Checkpoint:* About 20 per period, and about 1.31 per hold.

8.5 Theory and calculation · 7 min

For motions slow compared with the round trip, a wave channel whose slave end is held still behaves at the master as a spring of stiffness $2b/T$, the wave impedance over the one-way delay. Behind it the slave's PD and the wall add $K_{ser} = 1429\,\mathrm{N/m}$ in series.

(a) At a round trip of 500 ms, compute the channel's stiffness and the felt wall for $b = 20$ and $b = 50\,\mathrm{N\,s/m}$, and compare them with the 76 and 173 N/m measured in case 4. *Checkpoint:* 80 N/m and 75.8 N/m, 200 N/m and 175 N/m.

(b) With $b = 50\,\mathrm{N\,s/m}$, what wall does the same model predict through the 2.6 s of a lunar link? *Checkpoint:* About 37 N/m.

(c) Which wave impedance would the model need to render a wall as stiff as the 300 N/m hand at 500 ms, and what does a larger b cost in free space? *Checkpoint:* About 95 N s/m. The handle drags more in free space.

8.6 Theory and calculation · 6 min

In case 9 the operator moves and waits through a round trip of 2.6 s. Section 8.3.4 gives the rules: an increment of 10 mm in free space or 2 mm near contact, moved at 30 mm/s, then a hold until the video shows the slave within 1.5 mm of the aim, or until a round trip and a half and 0.3 s have passed, then a reaction time of 0.2 s.

(a) Estimate the time of one 10 mm step in free space, taking the video to show the slave's arrival one round trip after the aim stops. *Checkpoint:* About 3.13 s, against 3.15 s measured.

(b) Compute the longest time a 2 mm step can take, when the slave presses and the video cannot show it arriving. *Checkpoint:* 4.47 s, as measured.

(c) The 83 steps take 272.9 s. Find the mean time per step, and the share of a free-space step spent waiting for the round trip. *Checkpoint:* About 3.29 s a step, and about 83 %.

8.7 App challenge · 8 min

Load scenario 2, 100 ms of round trip, with the default seed, on the Channel view. Run at 1× until the run pauses after the third press, about 16 s on the clock, and read the Force reversals, Peak contact force and Energy created tiles of the scorecard.

(a) Report the three tiles, and when the status line first read Contact oscillation compared with when the ledger first turned positive. *Checkpoint:* 41 reversals, 25.7 N, 15.52 J at most, each within one unit of the last digit. The ledger turns positive at the first touch, two touches before the flag.

(b) Press Reset, set the Force reflection gain to 0.30 before pressing Run, and run until the run pauses. Report the same tiles, and whether the oscillation was flagged. *Checkpoint:* 9 reversals, 10.8 N, 110.3 mJ at most, within 1 mJ. No oscillation flagged.

(c) Is the channel passive at 0.30? Explain with the linearized limit of Section 8.5. *Checkpoint:* No. The loop is stable, since 0.30 is below the limit of 0.329, but the channel still creates energy.

8.8 App challenge · 8 min

Load scenario 5, A passivity controller at 500 ms, with the default seed. Run at 1× until the run pauses after the third press, about 21 s on the clock, and read the Peak contact force, Force reversals, Energy created and Damper dissipated tiles.

(a) Report the four tiles, and compare the energy created with the 9.54 J of case 3, the same delay without the controller. *Checkpoint:* 6.8 N, 8 reversals, about 3 mJ (the tile shows 2.9 mJ), 634.1 mJ, each within one unit of the last digit.

(b) Press Reset, set the Master damper limit to 50 N s/m before pressing Run, and run until the run pauses. Report the same tiles. *Checkpoint:* 7.8 N, 11 reversals, 274.3 mJ, 596.9 mJ, each within one unit of the last digit.

(c) Explain the difference between the two runs from Equation (8.12). *Checkpoint:* The clipped damper cannot take all of the excess, and the rest stays on the ledger.

8.9 App challenge · 9 min

Load the challenge, Four buttons and the peg at 400 ms, with the default seed. Each run ends when it pauses 2 s after the task is done, about 18 s on the clock at 1×. Read the Task, Peak contact force, Force reversals and Challenge target tiles. Reload the scenario before each new configuration and make the change before pressing Run.

(a) Run as loaded, with position–force at full reflection. *Checkpoint:* Done at 16.3 s, 108.8 N, 41 reversals, target not met.

(b) Set the Architecture to Wave variables and run. *Checkpoint:* Done at 15.3 s, 6.4 N, 15 reversals, target met.

(c) Set the Architecture to Model-mediated and run. Give the margins to the limits of 16 reversals, 10 N and 25 s, and say which of the two passing architectures you would put on a link whose delay may grow. *Checkpoint:* Done at 18.7 s, 4.1 N, 12 reversals. Margins 4 reversals, 5.9 N and 6.3 s.

8.10 Application area · 4 min

A surgical master is to move its slave at one fifth of the hand's velocity and to render the contact force five times larger, so that the surgeon feels fine tissue. Use the port powers of Equation (8.8) with no delay.

(a) Find the ratio of the power the channel hands the master to the power the slave takes from the site, and say whether such a channel is a wire. *Checkpoint:* 25. It is not a wire, and the ledger would book energy at every press and release.

(b) The slave moves $0.2\,x_m$ against K_{ser}, and the hand feels five times the force. Find the static loop gain $L(0)$ in terms of K_{ser}/K_h, and say what it means through a long delay. *Checkpoint:* $L(0) = 5 \times 0.2\,K_{ser}/K_h = K_{ser}/K_h$, the same as full reflection, so the bound of Equation (8.15) applies to the product of the two scales.

8.11 Application area · 3 min

A position–force teleoperator for a hot cell is commissioned with one operator whose grip matches the chapter's 300 N/m hand. Its gain is set to 0.20 for a link of about 500 ms.

(a) A second operator holds the handle loosely, at about 150 N/m. Compute the static bound for this grip. *Checkpoint:* About 0.105, so 0.20 is above it.

(b) Give two practices that keep the system safe across operators. *Checkpoint:* Commission against the softest grip expected, and watch the ledger rather than the reversal count.

8.12 Review the agent · 5 min

An AI assistant is asked how to protect a position–force teleoperator that will run on links from 100 to 1000 ms. It replies: "Use the status line as an interlock. When it reads Contact oscillation, set the reflection gain to zero. I checked it on case 2 at 100 ms, where the flag rises at 2.76 s and would have stopped the chatter." Find the flaw, and say how you would check it.