Robustness Analysis and Controller Synthesis for Bilateral Teleoperation Systems via IQCs

İlhan Polat

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CHAPTER 1

Introduction

The success of the technological advances often can be associated with an unprecedented convenience that they bring in. At the heart of this convenience lies the ability to relax the limitations of the human body to a certain extent. From this point of view, it is not a surprise that the three most prominent technological wonders of the last century, namely the *Television*, the *Telephone* and the *Radio* (which was originally called "radiotelegraphy"), bears the same Greek prefix *tele-* which corresponds to "*at a distance*" in our context. This shows that there is something of extreme importance about our drive to extend our capabilities beyond the constraints that our bodies impose.

It is quite remarkable, in retrospect, that these "gadgets" did not perish but rather kept on evolving since, initially, they were far from perfect. Quite to the contrary, they were hardly operational. Even the commercialized version of the early TVs had a narrow bandwidth and minimum image quality. Similarly radio and telephone was barely transmitting sensible information as far as the signal-to-noise ratio is concerned. Nevertheless, they have provided the ways of communication which were unimaginable before their time. Therefore the added value dominated the shortcomings and even though they were quite imperfect, we kept using them. The important lesson to be learned is that a technology should not be judged by its imperfections, but rather should be weighed by its contribution in this context and the convenience that is either immediately brought in by using it, or its foreseen potential by the "early adopters".

The success is also related to the fact that these technologies mainly relied on the human brain itself at their early stages. For example, the human brain did most of the noise filtering and data recovery by just guessing the missing pieces and identifying patterns from the signal brought by the respective medium. Today, with our smart mobile phones and 3D LED TVs, we can assume that the computational load, or whatever it's equivalence in terms of attention span capacity, on the human brain is drastically reduced. In other words, it is true that we are still identifying patterns and utilizing the relevant parts of our brain to make sense of a TV broadcast[1]. However, we do not need to use a higher level of concentration to reconstruct the words that we hear or to identify the image on the display thanks to the high quality output. We cannot exaggerate the importance of the human brain and its immersion power.

We are on the same track and leaving essentially the same footprints with the technological developments involving our touch sense. Though various science fiction items already used such ideas extensively, the real technology tends to follow

[1]Pun intended.

(a) (b)

Figure 1.1: Some historical details from the early mechanical television era: (a) Nipkow disc from Paul Gottlieb Nipkow's patent application, (b) Watching Television in 1928; the rotating perforated disc has 50 holes spirally placed, and rotates 18 times a second. Images are from [50, 77] respectively.

from quite a distance. Considering the importance of our sense of touch in any given situation, the added value of extending our perception in this modality needs no motivation. Take the most familiar, the vibrating mobile phone in the silent mode in our pocket. This is a very important example since every individual learns what that vibration might mean, either an SMS or a call, depending on the vibrational pattern. This means that the sense of touch can be used to convey messages that are not immediately related to physical act of touching. More importantly we can process those messages for inference which forms the basis of the so-called "haptics" and haptic technology.

The type of information from the cell-phone example is said to be received via the haptic channel (or the collaborative use of tactile and proprioceptive modalities). At this point we have to emphasize that, we use the term "sense of touch" rather vaguely as a shortcut and we leave it to the experts of the field to define the sophisticated mechanisms (pertaining to the somatosensory system) that we utilize when we manipulate objects, say with our bare hands.

Since our skin and muscles form one of most sophisticated and complex sensory systems, the somatosensory system, the brain can easily interpret the slightest changes and this extra signal processing power gives us a chance to hack into this system by providing artificial inputs via haptic displays. Still, it is rather conspicuous that it is impossible to achieve a total immersion with today's technology. The essential complication is twofold: the high sensitivity of the very same sensory system makes it difficult to fake or mimic a natural phenomenon by artificial means and on the other hand we do not have a well-defined mapping from the to-be-created sensation to the required excitation signals. Moreover, even if we have such mappings available, the related hardware must execute the computed haptic signal profiles perfectly which is generally not the case and a trade-off strategy should be constructed. In other words, we need a clear approximation metric to be able to compare two different touch technologies to judge whether one is better than the other. Unfortunately, this metric and thus the strategy is also absent.

Then, we could simply ask *Why bother?*

1.1 The Objectives

We first give a summary about the current concepts of the involved technology (as we foresee from a narrow "today's" perspective). Later on, we define our microscopic focus of this thesis within this vast generality. This would provide additional insights to what follows in the later sections.

Touch related applications are diverse. The diversity is not only in terms of the sensation they are related to (texture, shape etc.) but also how they encode the information and transmit via various modalities (e.g. vibrational patterns in mobile electronics, variable resistance to motion in game consoles and steering wheels etc.). There is no particular reason to limit ourselves with the daily needs or even luxurious demands regarding our touch sense as mobile phones taught us that a vibration in our pocket means a contact request from someone which is hardly ever related to the touch sense. It should be pretty awkward to experience if someone actually would come and shake our pockets to draw our attention (unless it is socially accepted). Therefore, we have devised a way to translate one particular message into another by simply teaching ourselves and getting used to it. Thus, it does not seem improbable that other types of physical measurements in terms temperature, light intensity etc., converted into pressure or tactile patterns in time domain.

Hence, it is our belief that the crux of this technology is establishing a interpretable protocol between our brain and the machine but not exactly reflecting the particular state of some distant or virtual physical medium. This would be the main argument of this thesis when we distinguish our approach with its comparable counterparts. For this reason, we have identified the nuances in Appendix B to narrow down our focus further by defining different types of touch related concepts.

Bilateral Teleoperation

Bilateral teleoperation, simply, is teleoperation equipped with force feedback to the human operator with the hope to increase the realism by recreating the force vectors of the distant medium at the local environment. The majority of the bilateral teleoperation research is devoted to kinesthetic feedback. In particular, the human interacts with the local device by moving a constrained handle to explore the environment or using a stylus-like stick. Hence, the experience is mostly based on the success of imitating a physical tool. Therefore, the tactile cues are of secondary nature. The challenge, of course, is to increase the performance level to a tactile display level while still maintaining the tool usage capability. The particular MIS tasks that are performed with a scalpel are one of the hot topics of research effort. It requires not only kinesthetic feedback, though a major accomplishment by itself, but tactile feedback too, for understanding the nature of the texture or the stiffness of the tissue. Similarly, teleoperated peg-in-hole type of tasks are also a major area of investigation; e.g., ground-satellite robotic mission directives or underwater construction tasks would benefit much from such possibilities to reduce the operational cost, duration, and success rate.

There are many interesting challenges when it comes to this recreation process. For example, in a microassembly task, the experienced forces are substantially different from what we feel during daily tasks. Gravity is our main source of reference when interpreting a distant location. However, gravity becomes almost negligible in the micro domain, as adhesive forces such as Van der Waals, electrostatic and surface tension forces dominate — the most common example is that the the parts that are picked up in microdomain tend to stick to the tweezers. Similarly in a space- or underwater- operation, there might be different forces that are not directly visible/interpretable by vision alone, say underwater currents or relative forcing between free bodies in space etc.

If we manage to create a believable level of force feedback sensation in these otherwise inaccessible domains, there are a few very important quasi-philosophical and also task-dependent questions that need to be answered. A few of these questions are:

- Should the device reflect the unfamiliar forces to the human operator for the sake of realism which are utterly counter-intuitive and even worse appear to be happening at random?
- Is there any correlation between increased realism and increased comfort? In case of a difficult task, what good does the realism bring in by replicating the difficult task at a distant location in the local environment?
- Do we need to reflect the human motion to the remote location perfectly since this can be considered as a waste of resources? In other words, we neglect the fact that a robot can perform certain tasks much more precisely than a human operator. Is there any downsampling/upsampling protocol to vary the motion precision depending on the receiver?
- If we decide to filter the irrelevant force information (e.g., mental/muscular fatigue, tremor on the operator side and measurement noise, nonlinear effects on the remote device side), how should we know what to transmit and what to filter out?
- Do we use the full capacity of our *internal data bus* to transfer touch information, or put differently, is there any space left to encode other quantities on top of the touch sense?

- Can we assume that all users more or less reach to the same understanding given a kinesthetic cue sequence?

These are interesting questions and answering them in a rigorous fashion is very challenging. The reason for enumerating a few of them here is that the problem is much more involved than what we can achieve within the scope of this thesis. In other words, we cannot, despite the recurring claims found in the literature, answer these questions within the scope of control theory/robotics alone. Instead we will focus on a framework that would help to set up such teleoperation devices such that experts in the involved fields can use these devices to answer those items above.

1.1.1 *Structure and Objectives of this Thesis*

To restrict the scope of this thesis further, we exclusively stay in bilateral teleoperation concept as we have defined it previously (via the classification given in Appendix B) and focus on the control theoretical aspects of the teleoperation for a stable interaction with sufficient performance levels. The reason of such a terminological classification is to precisely draw the boundaries of what will follow in the later chapters. Such a restriction is necessary to keep the discussion of the involved approaches/methodologies mutually exclusive which are often presented in a rather intertwined fashion in the literature.

In Chapter 2, we first give an opinionated version of the literature to point out to the underlying connections between seemingly different methodologies and also provide an arguably simpler explanation of the well-known *wave variables* formalism. By doing so, we classify such methods in the corresponding mainstream control theory methods and demonstrate that they are indeed outdated in the light of the recent advances. Moreover, we argue that the by-now-standard assumption of *passivity* property on the human and environment is not experimentally validated. We also claim that the success of passivity-based methods are due to the conservatism of these tests and not due to the validity of the assumption.

In a similar fashion, in Chapter 3, we enumerate the available performance objectives by which we should design bilateral teleoperation systems proposed in the literature. Then we argue why these objectives might not be valid candidates for the problem at hand.

In **??**, we also show both theoretically and numerically that the frequency domain methods (and a limited number of nonlinear methods) found in the literature can be combined under one framework via *Integral Quadratic Constraints* (IQCs). With these results, we demonstrate that the proposed approach of this thesis does not bring in additional complications or conservatism. In fact, via numerical case studies, we show that the results are precisely the same with those of the techniques available in the literature. Therefore, there is no fundamental reason to use a specialized terminology of the networks and microwave systems which in turn alienates mainstream control theory experts. We also remark that uncertainty modeling is a key aspect in obtaining better controllers for bilateral teleoperation. To highlight the reasons why we promote this framework, we also give examples of different combinations of uncertainties for which classical tools that are employed in the teleoperation literature are not suitable but already available in the robust control literature for almost two decades.

After establishing this link with the methods in the literature, we turn to the controller synthesis problem in **??**. We formulate the problem as a generalized plant and work out the scarce details that are found in the literature to obtain a better model- based control synthesis algorithm using static and dynamic IQCs. For the interested reader, we also explicitly identify what the implementation-related bottlenecks are. Then, in **??**, we utilize this framework to design controllers for an experimental setup.

In Chapter 4, we provide some concluding remarks and for the reader's convenience, in Appendix A, we recap the basics of the network theory.

Let us turn to our initial question "*Why Bother?*". We do because there is no need to obtain the ultimate, perfect touch sensation for the human in order to interpret the signals correctly. It is the same principle with LED TVs. Nowhere on the screen, a color different than red, green, or blue is emitted. However, we tend to approximate the combined output of the closely positioned RGB LED triplets to the closest color since the distance between the emitters are negligible for the viewer and we achieve the color perception. Therefore, realism is not our primary objective. However, before we can even enter the discussion of what leads to a satisfactory sense of touch, we need to make sure that the teleoperation devices, i.e., our tools that we actually try to understand the sense of touch with, are stable and exhibit consistent performance such that experts from neuroscience, psychophysiology, and other related scientific fields can join and assess different ways of protocolling with the human brain in this modality. Otherwise their conclusions would be contaminated by the device properties. We can even speculate that this is often the case, though no proof will be presented here.

Thus the precise goal of this thesis is first to show the state-of-art control problems in the literature regarding the bilateral teleoperation with a critical evaluation of the claims often found in various studies. Then, we consider the stability properties and control problem of bilateral teleoperation without fully understanding the underlying problem. Unlike many sources in the literature, we openly discuss the reasons behind the lack of understanding and clearly point out the vague performance objectives reported in the literature. The method adopted here and the application to an experimental setup constitute yet another stab at problem from a pure engineering/applied mathematics point-of-view. It is more general than the existing literature in the sense that the uncertainties and perturbations can be handled more systematically while defining performance objectives. However, this is not enough to argue that we have actually set up a beneficial and widely applicable framework that leads to a stable and high-performance bilateral teleoperation systems.

CHAPTER

2 A Brief and Opinionated Literature Survey

Teleoperation systems are structurally simple, two connected robotic manipulators, but equally challenging systems. This is especially true from a system theoretical point of view. As an example, if we just focus on the local and the remote devices that would be used for manipulation, we see that they are, whether linear or nonlinear, motion-control systems with well-studied properties. Hence, one can view the open-loop teleoperation, i.e., standalone devices without any communication in between, as a system with a block diagonal structure in which each input to this block effects only one of the devices. However, unlike the typical motion-control systems, these two disjoint systems must be stabilized simultaneously by the same controller[1], that is performing sufficiently well in order to "fool" the user such that the user feels a force feedback as if s/he is actually operating at the remote medium. With this structure, the outputs of either of these subsystems become exogenous inputs of the other and these are regulated by the to-be-designed controller. Therefore, it is this controller that makes a teleoperation system perform adequately or, as in many cases, drive to instability.

For example, in the case of the so-called *free-air motion*, i.e., the remote device is free to roam in the remote site, the human force input to the local device and/or the position of the local device should[2] be tracked by the remote device. In the case of a hard-contact of the remote device with the environment, however, these inputs should be counteracted if the force vector points into the obstacle. Hence, the force signal is simultaneously tracked for mimicking the user motion and is defied in case of a resisting force at the remote site. As if this is not challenging enough, when the user suddenly decides to release the local device, this resistance should die out as soon as possible, preventing a kickback. To sample the artificial nature of such a behavior, consider a user who leans to a wall located at position x_0 and beyond, applying a horizontal force and then retreating after some time. It is not expected that the wall continues to push the user even after the user has the position $x < x_0$. Such behavior would not only be unrealistic but also misleading as it can be confused with a sticky surface as far as the immersion is concerned. There are many other scenarios that would further complicate the requirements but, in short, the user and the environment properties are time-varying and make it difficult to

[1] We need to emphasize that the delayed/undelayed local control loops can be seen as the entries of a structured central controller. Thus, there is no reason to distinguish local control methods at this point.

[2] Or better, that's what we believe today.

design a straightforward control law such that these and many other details are handled properly, and more importantly, simultaneously.

With this short motivation, we can safely claim that looking at the overall system as a typical motion control system is not sufficient in terms of complexity (though necessary). In general, motion tracking specifications constitute a subset of the general performance requirements of bilateral teleoperation systems.

The inception of the bilateral teleoperation technology is often attributed to the work of Raymond Goertz in Argonne National Laboratories, [39] (in [6], it is traced back to Nikola Tesla and, in [116], even some 16th century tools are accepted as precursors of the contemporary teleoperation). The main motivation of Goertz' work (similarly later in Europe by Vertut [125]) was handling and manipulating nuclear material. Thus the very first teleoperators were purely mechanical to cope with hostile environment conditions. Though not much happened in terms of commercial product realizations, the concept of telemanipulation kept its appeal and a large body of research was reported until the 1980s. In that decade, with the help of the ever-increasing computational power and the popularity of Virtual Reality (VR), teleoperation technology received more attention for a possible use in the space-, underwater-, and medical-related tasks. Together with the advances in control theory and network theory (e.g. [36, 88]), a more systematic control methodology has been adopted. Especially, stability analysis results that can be related to design guidelines (physical parameter bounds, bandwidth limitations etc.) were utilized and limits of performance were explored. A particular phenomenon, namely the destabilizing effect of the delays in the teleoperation, lead the experts of the field to delve more into the systematic analysis tools and qualitative aspects of teleoperation. Especially, the use of the concepts such as, "passivity", "scattering transformations", and "wave variables" has become the standard methods of analysis and synthesis (see, e.g., [3, 40, 93]). Arguably, this point is where bilateral teleoperation branched off from the general control theory and became a specialized area of research, specifically dealing with a particular problem that is still a matter of unresolved debate, as we touch upon later in this chapter.

We start to summarize the advances from this point as this thesis is precisely built on top these systematic analysis and synthesis results gathered in the last two decades. However, the reader is referred to [13, 55], and [116] for a more detailed overview including other practical aspects of teleoperation analysis and the hardware developments with a more historical perspective which will be omitted here.

As we keep on narrowing down our focus to the control theoretical parts of this challenging problem, we have to note that many parts of the bilateral teleoperation problem can be scrutinized under different frameworks. Hence, there is no shortage of techniques for which the bilateral teleoperation problem is an ideal test case. In this plethora of methods, for example, the variation of human and environment properties give naturally rise to a robust or an adaptive control approach, the hard-contact problem can be analyzed by viewing it as switched control systems, jump control systems or constrained linear systems etc. Thanks to these advances,

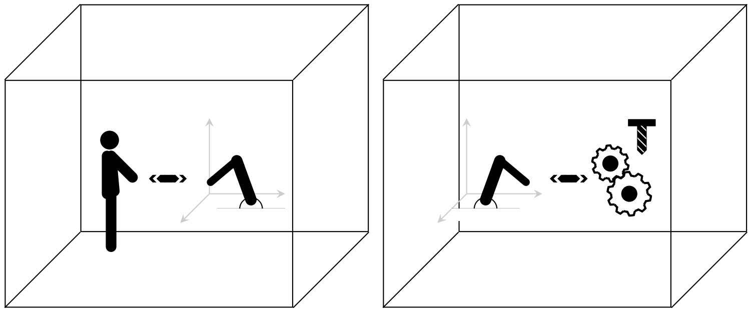


Figure 2.1: General Teleoperation System

as we elaborate, the main unsolved problem is not a methodological one but a motivational one. In other words we are lacking not the solution methods but rather a fundamental understanding of the problem in terms of what the requirements are and what a good device is if compared to another. Let us sample a few important and successful approaches reported so far together with their shortcomings if any.

We emphasize that the literature covered here is far from comprehensive and deliberately shaped with pragmatic intentions. Hence a large body of research is left out. This is certainly not due to their lack of thoroughness or else, but simply due to the irrelevance for the purpose of this chapter. In general, the methods that are left out either don't define a performance objective or only focus on the particular detail about bilateral teleoperation instead of the human perception. The reasoning behind this choice should be more apparent after Chapter 3.

2.1 Modeling of Bilateral Teleoperation Systems

The dominating modeling paradigm of bilateral teleoperation systems is the two-port network approach. Consider the following quote from 1989:

> The modeling approach is to transform the teleoperation system model into an electrical circuit and simulate it using SPICE, the electronic circuit simulation program developed at UC Berkeley. ([40])

As seen from Hannaford's motivation, the computer-based simulation tools are used extensively since then. Arguably, this is one of the main reasons why network and electrical circuit based modeling dominated the teleoperation literature. Reinforced with the circuit simulation tools, experts of the field started to construct analogies that go beyond a mere mechanical-electrical system analogy. Consequently, the most prominent concept borrowed from these analogies is the two-port network view of bilateral teleoperation systems. The reader is referred to Appendix A for a short recap of network theory. Today, the quoted convenience also applies to almost all physical systems, i.e., one can simulate arbitrary models via many computational packages. Yet, it's a de facto standard to use the circuit modeling while the teleoperation devices are mostly mechanical. Hence, it's not clear whether the benefit of such an artificial step still exists. Once the system is represented by a mathematical model, as it is demonstrated in the later sections, the mechanical/electrical analogy is, roughly, an equivalence based on the resulting model and works in the "from electrical to mechanical" direction too. Therefore, the circuit based modeling approach is merely a convention rather than a requirement.

2.1.1 *Two-port Modeling of Teleoperation Systems*

In the teleoperation context, if one uses the "load-source" analogy for the manipulated environment and the human, then the system models all the bilateral interaction between the load and the source ports (as in Figure 2.2a). This modeling view is quite powerful since the components are described via their input/output (or external) properties, i.e., across variable/through variable relations (e.g. force/velocity, voltage/current etc.). Also, the non/linearity properties of the components are not relevant at the outset if we are only interested in energy exchange, which is the basis of the so-called Time-Domain Passivity Methods [41] which we also mention later in this chapter. Thus, the user, the control system, the environment, the remote and local devices and the communication delays are seen as 1- and 2-ports exchanging energy in time. Since the external behavior of the ports can be characterized completely by the power variables associated with the terminals, e.g., voltage drop across the terminals and current flowing through them, it is indeed very convenient to model these components with electrical ports as interacting "black boxes" (See Figure 2.2a).

Remark 2.1. *We should emphasize here that, in this context, the energy exchange is used as a gauge of a potentially unstable behavior. The motivation relies on the fact that in order to classify a system as an unstable one, the system should exhibit unstable behavior at its port(s) and to exhibit such behavior additional energy is needed. Hence if all the components are incapable of contributing energy in the loop, finite energy excitations will eventually decay and the system would reach its steady state after a transient response*[3]*. As one can directly identify, this is simply the rough sketch of the celebrated passivity theorem. Based on this argument, there is a recurring theme in the literature that a teleoperation system should be passive in order to have a stable interconnection. This is due to the hypothesis that end terminations are also passive. However, in a few studies, this is mistakenly taken as a sufficient and necessary condition for stability and hence creates quite some confusion for the non-experts of the field. Passivity is not an essential feature of the teleoperation systems but only a convenient shortcut for deriving interconnection stability conditions. We should iterate that stability is the top-priority objective and does not require passivity by any means even if we do guarantee stability by rendering the sub-components passive.*

[3]For the sake of brevity, marginal stability or limit cycles also require extra energy for the sustain.

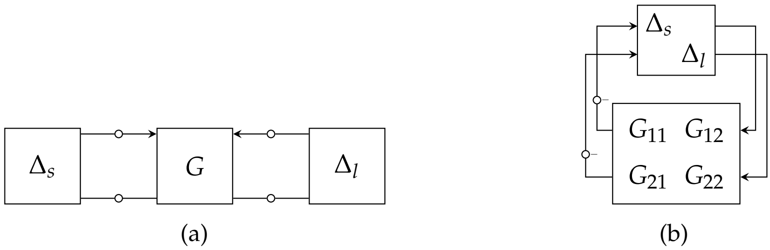


Figure 2.2: Two representations of a 2-port network. Here Δ_s and Δ_l represents the source and the load immitances respectively. In the teleoperation context, they are the human operator and the explored environment.

Clearly, thanks to this modeling method, we don't even need to know exactly what Δ_l, Δ_s blocks are, except their class (e.g. linear/nonlinear, time invariant/time varying etc.) to analyze the interconnection via G and its port behavior. Thus, the problem of modeling of the human arm or of the uncertain environment is circumvented. However, with the same reasoning, the passivity property does not distinguish particular systems as long as they are passive. That is to say, some of the crucial information is lost about these specific ports; we discard any impedance or admittance relations shared by the port variables.

Energy based modeling is also the natural basis of bond-graphs. Bond-graphs, much like port representations, are graphical tools to model the dynamical systems via energy balancing between subcomponents (See [37] for an introduction). In other words, the bond-graphs are built on top of the notion of bonds representing the instant energy or power exchange between nodes via edges drawn between them. Therefore, bond-graphs already present a powerful framework for the abstraction of the bilateral interaction between the local and the remote site. For a classical use of bond-graphs in impedance control, the reader is referred to Hogan's trilogy ([52–54]). There are also many studies with application focus, e.g., [72] using hydraulic systems for bilateral teleoperation, among many others.

2.1.2 *Assumptions on the Local and Remote "Ports"*

As mentioned above, network theory offers a great opportunity for modeling teleoperation systems, or better, avoiding a refined modeling. Still, to invoke the stability analysis and synthesis results of network theory, there is a need to distinguish Δ_s, Δ_l further in the universum of 1-ports. Otherwise, with no additional assumptions there is not much we can conclude from such an interconnection since they can be any arbitrary model with arbitrary behavior set as long as they respect the port condition. This is obviously a crude approximation of the real physical interaction that teleoperation systems exhibit.

In the teleoperation and haptics literature, it is customary to assume the load and the source terminations as "passive" mathematical operators (see Appendix A).

Starting with this hypothesis, the stability problem can be converted to a typical energy dissipation problem. Hence the view of the designer is tuned to look out for the energy sources and interaction between two distant media. This approach treats the human and the environment as passive 1-port circuit elements together with additional voltage and/or current sources modeling the intentional force input to the system. The controller(s) act as the energy regulator preventing excess energy generation to avoid a possible instability even in the cases where extra energy does not endanger stability or in fact needed by the user to accomplish certain task or stabilize the system.

Additionally, as summarized in Appendix A and in **??**, one can use the network theory based conditions to assess the stability and performance conditions thanks to this hypothesis.

This brings us to the discussion of the justification of the assumption as it is generally not given in full generality in the literature. Is it indeed calid to assume that the human can be modeled as a passive system? If one scans through the literature about the passivity of human operators, it is the Hogan's paper [51] that is almost universally cited. The striking detail is, however, that Hogan never claims that the human hand/arm is a passive system. Instead he clearly shows that under very specific conditions, human behavior is indistinguishable from that of a passive system:

> Thus, despite the fact that the limb is actively controlled by neuro-muscular feedback, its apparent stiffness is equivalent to that of a completely passive system. In the light of Colgate's recent proof [3][4] that an apparently passive impedance is the necessary and sufficient condition for a stable actively-controlled system to remain stable on contact with an arbitrary passive environment, this experimental result strongly suggests that neural feedback in the human arm is carefully tuned to preserve stability under the widest possible set of conditions.

Moreover, the task reported in the paper that is given to human operators and analyzed afterwards, can be considered as a biased one because the success of the test is related to the passive behavior of the human. The task is, roughly speaking, holding a handle which is perturbed by random disturbances and trying to keep the handle still at a predefined position on the 2D plane. Hence, the task is simply to mimic a passive system. Had it been the case that measurements on the human arm would exhibit a non-symmetric stiffness matrix in the arm model, it would simply be a failure of the test subject (regardless of the physical limitations of the human arm in general). Note that this is a plausible situation for rehabilitation tasks. The other possibility would then be that the test subject was unable to keep up with the changes, or using the control theory jargon, the bandwidth of the subject

[4] Reference [22] of this thesis. However exactness of stability characterization for two LTI passive complex uncertainty blocks was already well-known in SSV theory (e.g., [98]) and also in the classical network theory works at the time of writing. Therefore it is a misattribution.

was lower than the required agility to perform the test adequately. The well-known phenomenon due to such human input is the "pilot induced oscillations" in which the pilot of an aircraft, while trying to stabilize the aircraft, via overcorrecting inputs, destabilizes the system due to many distinct reasons (the phase lag of the pilot, response time of the aircraft etc.). We refer to the interesting report [83] for a more detailed exposition. Also, if for some reason, the task at hand is to prevent the system to reach a steady state at a certain position and the perturbations are applied accordingly i.e., to create a virtual negative potential, the results obtained from the experiments would most probably differ from that of [90]. Thus, it's emphasized here that the passivity of the human is closely linked to the requirements of the tasks.

Remark 2.2. *A particular detail should be clarified about the measurements taken in [51]. It is stated that:*

> *While normal human subjects held the handle of the manipulandum at a stable position in the workspace, small perturbations were applied. Measurements of the human's restoring force were made after the system had returned to steady state following the perturbation but before the onset of voluntary intervention by the subjects.*

Therefore, it is emphasized that only the involuntary response is taken into account during the measurements in order to capture the natural properties of the human arm before the human correction intervenes. In fact, due to this crucial distinction the results such as [31] don't disprove Hogan's results since the voluntary input is included in the model.

We believe that it is unaviodable to introduce some concepts from the muscle physiology in order to put Hogan's argument into some mechanical engineering perspective. It is simply impossible for us to give a detailed analysis, however, mentioning the involved process via some mechanical analogies in order to relate the results of Hogan and Mussa-Ivaldi ([90]) seems feasible. This would emphasize the reason why we think that the common inference from their experiments in the literature is not inline with the conclusions of these studies. We refer the reader to the physiology literature e.g., [38, 56, 85, 95, 119, 130] and references therein for a full treatment. Hence, we will only give a rough picture about the apparent behavior. Nevertheless the point that we want to emphasize is, fortunately, not related to the inner workings of the human muscles.

The skeletal muscle activation takes place via a process described by the *sliding filaments model* (Figure 2.4). The muscles consist of muscle fibers and muscle fibers are made up of *myofibrils*. The myofibrils involve different types of thin and thick filaments, mainly of the type *actin*, *myosin* and *titin* filaments. The myosin filaments involve extensions that can bind to the thin actin filaments. The relative motion of these filaments are produced due to these extensions via ATP hydrolysis. Moreover, these extensions stay connected or disconnected to actin filament unless more ATP is utilized. Hence, the muscle needs extra energy to relax which is the reason behind

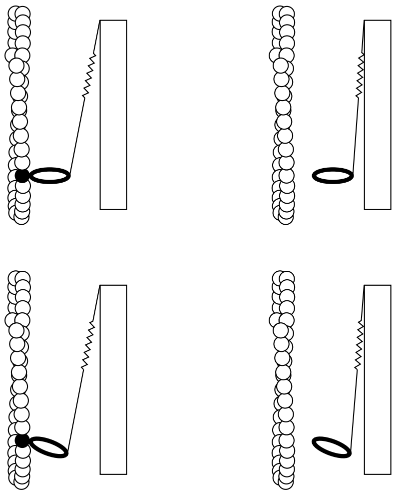


Figure 2.3: Muscle activation mechanism (adapted from [38])

"*rigor mortis*" and some types of the muscle spasms when this additional energy source can not be provided or ATP can not bind to the actin filament for some reason. Moreover, binding or detachment of these extensions is also regulated by the Ca^{++}, Mg^{++} concentration in the muscle cell and controlled, eventually, by motor neurons using yet another chemical trigger.

Therefore, the individual muscle activation at the basic level is analogous to a clock escapement mechanism [46] i.e. each time the lever arm pulls back a thread of the gear and the cycle repeats. The resulting relative motion is very much like a graphite coming out of a mechanical pencil when pressed from the eraser cap. Obviously, muscle behavior is not rachet-like but smooth. This is because each of these mechanism operate independently. Thus, at each time instant, different myosin extensions can be found at different phases of the cycle very much like a helical gear pair that are always in contact at one point. Using this analogy, ATP molecules are used to open and to close the pencil clutch made up of myosin extensions and actin filament is pushed forwards. Moreover, titin filaments can be thought of as the connecting rod of the pencil from the cap to the clutch which is mostly responsible for the passive elasticity of the muscles.

In summary, the muscles have varying non/backdrivable configurations. Moreover, we can lock our muscles in place e.g., we can try to keep our arm at one position during drilling etc. to increase the precision. Then, the arm becomes a stiff object with inherent stiffness of the connection rod (titin), pencil clutch (myosin actin), muscle tendons and various other involved processes resisting to the applied strain.

Coming back to our original discussion, the stiffness of the arm that has been the subject of the experiments mentioned above is, again invoking the analogy, based on the closed clutch response of the arm. In other words, what is measured is a

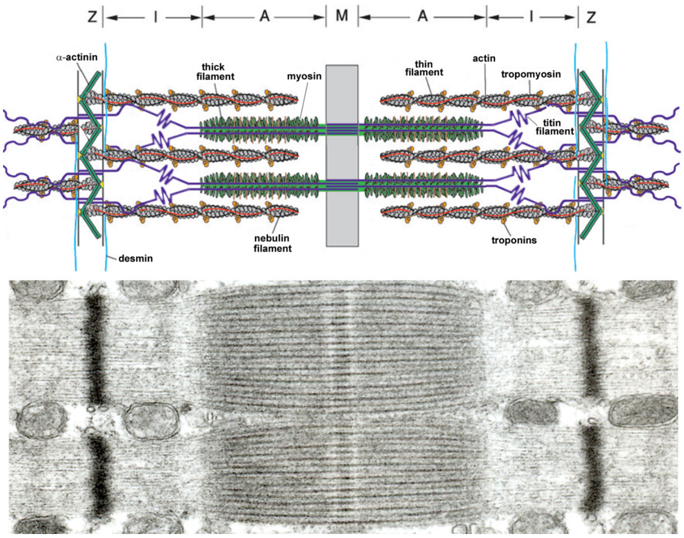


Figure 2.4: The simplified illustration of the sliding filaments model for a single sarcomere. (Source: [96])

cumulative spring-like behavior of the arm that is actively controlled to be kept at a certain configuration. This is related to the "human's restoring force" given in Remark 2.2.

Having a spring-like property naturally implies that the arm is passive. But the problem with this argument, as far as we understand, is that there is no reason to assume that the human arm model involves a symmetric positive definite stiffness matrix at each time instant for an arbitrary trajectory. In fact, as shown clearly in [90], the major eigenvector of the stiffness matrix varies both in terms of direction and magnitude. Therefore, it might be possible to extract energy from the human arm with some particular pathological trajectory. Just in the case of a frozen time analysis of a time-varying operator does not imply stability, the conclusion is only valid for postural analysis at a fixed configuration of the human arm but not for an arm trajectory.

Therefore, it is our belief that the assumption of human arm being a passive system is incorrect for most teleoperation tasks.

Since it is customary in the literature to include the passivity hypothesis, let us invoke it here too for the sake of the argument. The question of how, then, a human can possibly move anything while remaining passive is one that makes the whole story even more complicated. The voluntary input of the human is taken as an exogenous and state independent input to the system. Hence, the human cognitive input is an additional but independent force source acting on the handle together with the passive human arm immitance as depicted in Figure 2.5. In other words, the contribution of the exogenous force and the arm dynamics are assumed

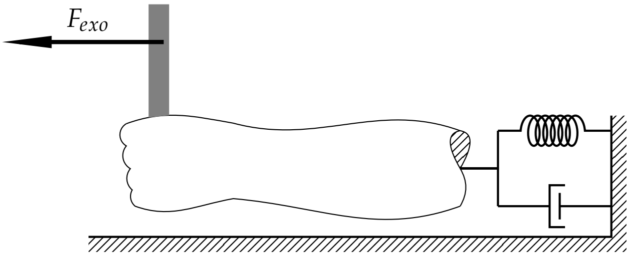


Figure 2.5: A pictorial representation of the state independent human force input. By state dependence, we mean that the vector F_{exo} is completely decoupled from the arm characteristics and can be taken as a genuine exogenous input.

to remain mutually exclusive.

The reader would spot that this is not in line with Hogan's remark since the activation state in the muscles should be altered in order to apply some force. In other words, we need to alter the stiffness matrix of the arm to be able to move but, to the best of our knowledge, this is not given in any teleoperation study. In other words, the answer to the question of whether the human's restoring force would exhibit the same properties during the force exertion phase is not known to us. It has been also shown that the applied force is also related to the muscle tension-length properties [57] which we have not considered in our analogy.

Therefore, we have to further separate the human force into two parts, namely, the active neuromuscular feedback force that keeps the human arm passive and the voluntary and cognitive force input applied to the system. How this is usually performed is not clear in the literature. To the best of our knowledge, this issue is considered (but still briefly) only in [63, Sec. II.B] and references therein.

This ambiguity becomes much more important since the control oriented focus of this thesis necessitates that we concentrate on worst cases rather than the experiments performed within the cognitive range of human operators. In other words, we are interested in the cases where things go wrong due to various reasons, such as sampling disturbances, measurement noises, directionality etc. Therefore it cannot be a satisfactory argument if stability depends on the user's neuromuscular feedback or, simply, the user's stabilization capabilities. In order to use the bilateral teleoperation devices in real-life, stability should be addressed regardless of the set of prescribed human actions. Hogan's findings are not sufficient for supporting the passivity assumption often found in the literature.

In summary, the passivity of the human and the environment (or the virtual environment in haptics/virtual reality applications), is only plausible in certain cases; then it should be verified regardless, in order to assume that the corresponding mathematical models are passive. Still, analysis and synthesis methods that invoke this assumption lead to many real-world implementations with varying degrees of realism. An obvious follow-up question is "how can then the reported analysis and synthesis results based on this passivity assumption lead to successful implementations which would imply the validity of the assumption?". We need to focus on the "successful" part in order to answer this question. If we again scan through the literature these successful implementations are only successful under strict assumptions about the user behavior together with any combination of the following device properties

- The controller stabilizes the loop via excessive apparent damping hence either or both free air or hard contact realism is lost.
- The bandwidth of the force and position tracking are exceedingly small.
- The remote and local devices exhibit position drifts over time.
- The performance of the device is time-varying and not uniform.

We argue that the success of these methods is due to the conservatism of the analysis/synthesis tools and does not validate the passivity hypotheses on the respective models. Many frequency-domain methods, which assume LTI terminations at both ends of the teleoperation network, are reported to achieve stable bilateral interaction in real setups. While impressive, this shouldn't have been possible had the tests not been exceedingly conservative since the real setups involve sudden contacts i.e. they are essentially time-varying systems. We recall the well-known fact that the behavior set of the time-varying systems are significantly richer than LTI systems. Once again, we remind the reader that the proper metrics to gauge the success of teleoperation systems are not known and we use the typical error-norm based control design rationale.

A compact version of the argument above is given by Yokokohji and Yoshikawa in [132]:

> Passivity of the system can be a sufficient condition of stability only when the system interacts passive environments. In the case of master-slave systems, if we could assume that the operator and the environment are passive systems, then the sufficient condition of stability is that the master-slave system itself must be passive. Strictly speaking, however, the operator is not passive because he/she has muscles as the power source. Colgate et al. [21][5] mentioned that even if the system has an active term, the system stability is guaranteed unless the active term is in some way state dependent. Obviously, the operator is passive when $\tau_{op} = 0$. Therefore, we will give the following assumption about τ_{op}: "*The operators input τ_{op} independent to the state of the master-slave system. In other words, the operator does not generate τ_{op} that will cause the system to be unstable.*" Dudragne et al. [3][6] gave a similar assumption in order to use

[5] Reference [22] of this thesis.
[6] Reference [29] of this thesis.

> the concept of passivity for stability distinction. The above assumption seems tricky in a sense, but it is necessary to ensure the system stability by the passivity.

Finally, a supplementary remark is also given by Buerger and Hogan in [11]:

> When passivity is used as a stability objective, the only assumption made about the environment is that it, too, is passive. This is likely sufficient to guarantee coupled stability with humans (though, to date, it has not been conclusively proven that human limbs are passive; see [29][7] for an argument for treating them as such). However, given the properties of human arms described above, passivity is unnecessarily restrictive. Our experience has shown that some controllers that are known to be nonpassive are adequately stable in clinical rehabilitation tasks [26][8].

We should mention here that Hogan's paper together with other identification experiments are extremely important for many fields and needs no motivation. The discussion above only points out that the frequently reported inference that follows from his results is not in line with the results.

The idea of modeling the teleoperation as a two-port network seems to have multiple origins and we have no reference to point out a common source. However, in general, the popularity of two-ports can be attributed to [3, 40, 93, 105, 132].

2.1.3 *Uncertain Models of Bilateral Teleoperation for Robustness Tests*

Another possibility of modeling the human arm and its cognitive input is to define a reference position signal "filtered" by the human arm impedance[9] e.g., [63, 79]. Various studies pointed out that the identification experiments suggest a mass-spring-damper system pattern is evident in the frequency response data of the human arm recorded under various task performance similar to the one given in [51]. The general method is to instruct the human to perform a specific task and then perturb the hardware with certain predesigned disturbance signals such that the output can be evaluated to obtain a mathematical model. In the literature, the model structure is often set a priori to be a second order transfer function and the parameters are optimized to minimize the mismatch between the experimental and predicted response. It is also well-known that the human can change the inherent impedance of the arm during the task execution (see, e.g., [123]). Therefore, the studies are performed in the ranges where it is safe to assume that the human arm characteristics are constant or constant up to negligible changes.

[7] Reference [51] of this thesis.

[8] Reference [12] of this thesis.

[9] The term *impedance* is used in a more general sense than its common usage to denote LTI transfer functions such that no distinction is made between linear and nonlinear or time-invariant and time-varying operators.

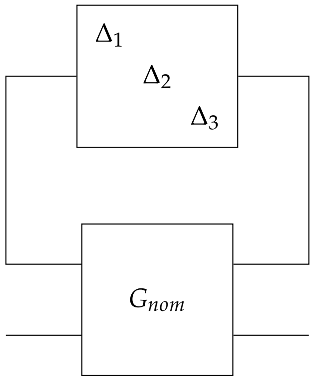


Figure 2.6: Uncertain model representation by taking out the uncertainty blocks

The modeling is straightforward via uncertain mass-spring-damper system differential equation manipulations. Suppose the human arm admits the second order model

$$M(\Delta_1)\ddot{x} + B(\Delta_2)\dot{x} + K(\Delta_3)x = F_h - F_m$$

where F_h, F_m denote the human force and the force feedback inputs, respectively. Then choosing a multiplicative or additive uncertainty structure and via basic linear fractional transformations, the signal relations are converted to the interconnection shown in Figure 2.6. The arrows are deliberately left out as it is up to the designer to get different immitance models.

Many studies have appeared in the literature regarding such modeling and the majority of these assume a mechanical model of order from two to five. Note that this is an assumption made a priori and only applies to the specific task performed by the human in the experiment from which the frequency response data is collected. The commonly utilized models, unfortunately most given for the fixed postural arm configuration can be found in [4, 11, 24, 35, 58, 63, 71, 76, 80, 118, 122]. Obtaining these measurements are time-consuming and difficult to parameterize. For this reason, although the results along this direction are scarce, they are, as in the passivity case, very valuable.

The disadvantage of such parametrization of the human arm is contrasted with the passivity approach methods invoking the argument of the time-varying nature of the arm parameters. It is often rightfully argued that the uncertainty ranges in which the stiffness and damping (and partially inertial) coefficients change, are too large to be considered in the structured singular value based robustness tools. Moreover, many auxiliary effects such as the visual feedback, cognitive lag of the brain etc. are not considered in the identification experiments; in the passivity approach all of these are lumped into a single port condition. Obviously, the main difficulty is to get a model (out of hypothetical insights, identification experiments etc.) which is not required in the passivity approach.

The papers [79, 103] offer interesting alternatives for human modeling as they attempt to incorporate many of the aforementioned effects, but the results are prospective and yet to be utilized.

2.2 Analysis

The stability analysis is one of the major problems in designing stable yet high-performance teleoperation systems. It's often not feasible to manually tune some local controllers and make test subjects use it in order to verify the design specifications. Moreover, by relying only on the experiments, one can miss an important destabilizing scenario if the field experiments do not cover that particular case. Hence, an a priori certificate of stability is much sought after. The stability analysis can also give some guidelines about the parameter selection in the hardware design phase and can lead to minimized design iterations. Therefore, having a realistic stability test is essential in building these systems.

Similar to the modeling section, the analysis in the literature extensively relies on network theory based results. In fact this is where the network theory stands out as a complete tool for analysis and synthesis of bilateral teleoperation systems via the hypothesis that human and the environment models are passive.

The common terminology for stability is somewhat different than that of the contemporary control theory as *nominal stability* is used for the stability properties of isolated two disjoint media; when the interaction is set up between these two media the closed- loop stability problem is called *coupled stability*. To the best of our knowledge, this terminology is introduced in [22] hence we refer to this paper (or Colgate's thesis [21]) for more details.

It's also worth mentioning that the passivity and stability is used often interchangeably and also usually referred to the classical texts [16, 45, 87] for the precise definitions. Hence, there is a little guesswork required to classify the stability definitions given in the literature in order to locate which version is meant. The important distinguishing point is that marginal stability is often accepted in the definition of stability results since it arises frequently in lossless (hence passive) models where energy conservation is assumed. However, the analysis results that rely on such assumptions do not guarantee asymptotic interconnection stability, but only lead to certain passivity properties of the interconnection (see [64, Thm. 6.1] and [78, Sec. V] for the discussion on strict passivity).

As given in Section 2.1, the passivity property is crucial to many studies in the literature. The direct physical interpretation of the abstract concepts gives even more appeal to such energy book-keeping methods. Another advantage of passivity methods is that the nonlinear counterparts of the results are also available in the literature and relatively easy to utilize. However, this convenience misses out many relevant details that are specific to teleoperation systems and result with too general conditions. Let us recall a general version of the passivity theorem:

Theorem 2.3. *The negative feedback connection of two passive systems is passive. The neg-*

Figure 2.7: A transparent two-port network with passive terminations. The actuation of the railcar is taken as a state-independent input to the system. (Source: Fred Dean Jr., [Flickr:Fred Dean Jnr])

ative feedback connection of a passive system with a strictly passive system is asymptotically stable.

Note that, this result is valid for both nonlinear and linear systems. Invoking the theorem twice on the teleoperation system allows us to conclude that, under the passivity assumption of the human and the environment, if the two-port is passive then the interconnection is passive. Moreover, if any of the involved operators is strictly passive the teleoperation system is asymptotically stable.

The passivity theorem is in general not necessary for stability but only sufficient. Because there do exist stable interconnections that involves nonpassive subsystems. In particular, the conservatism brought in by passivity assumption is arbitrarily high (especially in the nonlinear case). Facetious as it may seem, the test also takes into account the port terminations shown in Figure 2.7 for a table-top joystick. We have to emphasize that the three-carriage railcar with two cabs, is a valid, almost perfectly transparent two-port network with passive end terminations. Hence, a regular passivity-based stability test includes those end terminations for a simple hand-held device. In other words, if we only consider the passivity property of the involved subcomponents and do not distinguish further, there is no possible way to distinguish a table-top teleoperation system from a train since both are passive. It's that conservative.

The major disadvantage of the passivity methods is that the procedure is focused almost only on the energy exchange. The performance specifications are very difficult to formulate and also difficult to integrate into the analysis and synthesis steps using only the inner product structure. As an example, the signals that are not port variables such as position errors, nonlinear effects etc., that are functions of these signals, can't be utilized easily in the performance specifications. Same difficulty arises in the normed space structures though much more can be achieved. Similarly, peak-to-peak gain minimization methods are not mature enough to handle any practical system without excessive conservatism.

Another disadvantage is that the power- or the energy-based analysis, due to the inner-product structure, can not distinguish the individual signals. Consider the ideal case where the human and the local device is pushing each other and cancelling each other's contribution. In this case the external or observable energy exchange based on the port variables is zero (negligible) which can not be distinguished from the case of not touching at all (a small motion on the device).

When the network, human, and the environment models are assumed to be Linear Time Invariant (LTI), the frequency domain methods allow us the analyze the teleoperation systems for stability and performance. The most common stabiliy analysis tool for such models is the Llewellyn's stability criteria (also often called absolute stability theorem or unconditional stability theorem). For linear networks, the following definitions seem to be used quite widely (modified from [16]):

Definition 2.4 (Potential Instability). *A two-port network is said to be potentially unstable if there exist two passive one-port immitances that, when terminated at the ports, produce a persisting natural frequency.*

Definition 2.5 (Absolute Stability at $i\omega_0$). *A two-port network is said to be absolutely stable if it is not potentially unstable.*

2.2.1 *Llewellyn Stability Criteria*

The well known conditions for stability of a two-port network, formulated in [10, 81, 107], are recalled in Appendix A. As shown in [107], the conditions stated in Theorem A.7 are invariant under immitance substitution. This result forms the basis for almost all passivity-based frequency domain bilateral teleoperation stability analysis approaches in the literature. We also derive this theorem from an IQC perspective and show that it is actually the passivity counterpart of the of the D-scalings in the μ-tools. This has also been derived in a scaled teleoperation context in [102] using only Structured Singular Value (SSV) arguments.

Thanks to the frequency domain formulation, it is possible to rewrite the condition (A.12) as a fraction and see the problematic regions in which the fraction gets close to or crosses to the instability, together with one of the conditions given in (A.11).

2.2.2 *μ-analysis*

As given in Section 2.1.3, stability in the face of uncertainties can also be analyzed in the generalized plant framework of robust control. After rewriting the signal relations, the teleoperation system can be written as an uncertain interconnection as shown in Figure 2.9. In this setting, G is the model of the nominal bilateral teleoperation system and Δ is a block diagonal collection of uncertainties, such as the human, the environment, delays, etc. Stability tests are based on structural

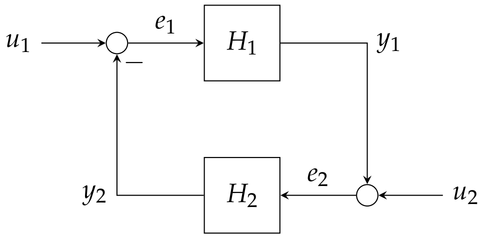


Figure 2.8: Negative feedback interconnection

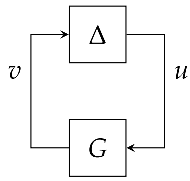


Figure 2.9: Uncertain Interconnection

hypotheses on the diagonal blocks of the operator Δ such as gain bounds or passivity. These properties should allow us to develop numerically verifiable conditions for the system G that guarantee interconnection stability. This is intuitive because we have no access to the actual Δ and we can only describe its components by means of indirect properties.

If the interconnection subsystems are represented in the scattering parameters, the μ test is precisely equivalent to the test of Llewellyn's theorem and often called as Rollett's stability parameter. This is due to the well-known equivalence between the small-gain and passivity theorem [27]. We have to note that the equivalence is stated in terms of the stability characterization. Otherwise, the small-gain theorem requires a normed space structure whereas passivity theorem requires an inner product space structure, hence the applicability is relatively limited. This is also related to the fact that we need to work with power variables exclusively in the passivity framework and this is not always convenient if the performance specifications are related to other variables.

In the literature, this analysis method often follows the scattering transformations such that, the passivity assumption avoids the explicit modeling and then small-gain theorem is utilized mainly to handle the delay problem via with the involved norm bounded operators. A refinement can be found in [102] where the authors utilize a direct μ-analysis to reduce the conservatism, however rather remarkably, it's not picked up by other studies and the analysis is mainly limited to small-gain conditions even in the linear systems.

We could have also directly choosen to utilize the uncertain modeling of the human and the environment and utilize μ-analysis for the teleoperation system had the specific models been available.

2.2.3 *Modeling the Communication Delay*

Over the past two decades, it has been confirmed in various studies that, if present, communication delays are a major source of instability (reports date back to 60's, e.g., [115] and the references in [3]). Even when the delay duration t is known and constant, the delay operator can be shown to be nonpassive since e^{-st} is not positive real. Hence, when combined with the passivity framework, it violates the assumptions on the uncertain operators.

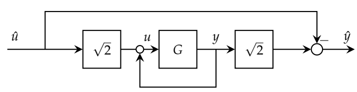
At end of the 80's and early 90's, two prominent studies ([3, 93]) proposed to handle the delay robustness problem using scattering transformations. This notion is best explained, in our humble opinion, by loop transformations since the original articles refer to microwave and transmission line theories which use quite specialized terminology. One can also find a slightly different system theoretical view of these transformations in [23]. If we restrict the discussion to LTI operators[10], the key concept of the scattering transformation or the wave variables methods is to map the closed right half plane to the closed unit disk via a special case of bijective Möbius (or linear fractional or bilinear) transformation:

$$W : \mathbb{C}_+ \cup \mathbb{C}_0 \mapsto \{z \in \mathbb{C} \mid |z| \leq 1\} \ , \ W(z) = \frac{z-1}{z+1} \tag{2.1}$$

One can directly verify that $1 \mapsto 0, \infty \mapsto 1$ and $0 \mapsto -1$ under W. Pictorially, the mapping is given in Figure 2.10 using a Smith chart which is located at the origin. Hence, positive real transfer matrices become norm bounded by 1 such that we can analyze the interconnection using the small-gain theorem.

Let us demonstrate a few properties of this transformation. First, this mapping can be shown with a block diagram. Assume that G is a proper positive real LTI SISO system and let the input/output relation be given by $y = Gu$. Then, with a standard manipulation, we obtain a feedback interconnection that leads to the mapping

$$W(G(s)) = \frac{G(s)-1}{G(s)+1} = -1 + \frac{2G(s)}{G(s)+1} \implies$$



(2.2)

Simply following the signal paths, we also see that the input/output relation becomes

$$\tilde{y} := W(G(s))\tilde{u}.$$

where

$$\begin{pmatrix} \tilde{y} \\ \tilde{u} \end{pmatrix} = \sqrt{2} \begin{pmatrix} -1 & 1 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} u \\ y \end{pmatrix} \tag{2.3}$$

Note that, physical realization of this transformation requires a simple feedforward and a feedback control action to which typically referred with *"Wave encoding"*.

[10] In the nonlinear case, it's a *completion of square* argument to switch from the inner product structure to a norm structure provided that the signal space is suitable for such operation.

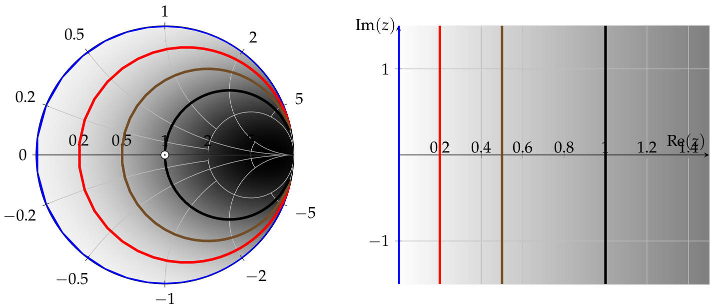


Figure 2.10: Mapping the closed right half plane onto the unit disc.

Often these variables are normalized with $\sqrt{2}$ at the outset. The seperation of $\sqrt{2}$ blocks is a matter of convention and provides symmetry in the block diagrams. Also we have,

$$\begin{aligned}(W \circ W)(G) &= \frac{-1}{G},\\ (W \circ W \circ W)(G) &= \frac{-1}{W(G)},\\ (W \circ W \circ W \circ W)(G) &= G\end{aligned}$$

which shows the effect of the $90°$ clock-wise rotations of the Riemann sphere about the axis parallel to the imaginary axis (W is an element of Möbius group with $\circ$ operation). This stereographic projection idea is also the main idea behind the derivation of the stability parameter of Edwards and Sinsky ([32]).

Obviously once this transformation is introduced, there is a need for the "inverse" of W on the operator that is seen by the operator G such that the loop equations remain unchanged, that is to say we have to introduce another transformation that undoes W. The simplest way to obtain a mapping $\hat{W}$ is to follow the block diagram backwards as shown in Figure 2.11. A block diagram reduction step(or rotating three more times as shown above) shows that

$$\hat{W}(z) = -\frac{z+1}{z-1} = -\frac{1}{W(z)}$$

which is nothing but the inverse of the relation (2.3). The negative sign usually does not show up in the formulations in the literature because the passive interconnections require a sign change in the loop to indicate the "from" and "to" ports. A more detailed derivation is given in [23]. Also note that a positive real transfer matrix, when negated, has its Nyquist curve confined to the close left half plane (anti-positive real) which is equivalent to a $180°$ rotation or application of W to the closed left half

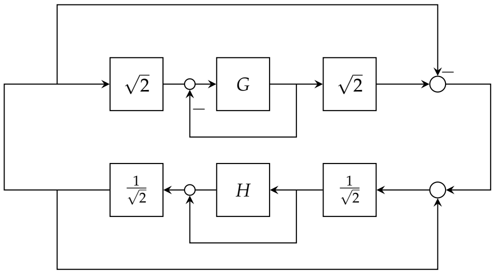


Figure 2.11: Scattering transformation and its inverse.

plane twice. Thus, some care is needed for the book-keeping of the negative signs and seemingly the best practice is to absorb the negative sign into H at the outset and work with $-H$ afterwards. This makes the required forward and backward transformations in the loop identical. One can see that there are many variants of this mapping, especially in wave variables context, e.g., $\frac{z-b}{z+b}$ but for simplicity we take $b = 1$ as it doesn't play any role in our presentation of the method.

Under the mapping W, the Nyquist curve of e^{-sT} (the unit circle) is mapped onto the imaginary axis, and hence unbounded, i.e.

$$\frac{e^{-i\omega T} - 1}{e^{-i\omega T} + 1} = i \tan \frac{\omega T}{2}$$

One can also obtain a similar qualitative result by seeing the unit circle $\mathbb{T}$ as the image of the imaginary axis under W:

$$W(\mathbb{T}) = (W \circ W)(i\widetilde{\omega}T) = \frac{1}{i\widetilde{\omega}T}$$

We don't need to track the points individually as we are only interested in the domain and its image under these transformations.

Therefore when we connect a passive operator to a small-gain operator, neither small-gain nor passivity theorem can be applied directly since each operator is not in the class of the other operator. In other words, delay uncertainty does not satisfy the norm constraint $\|W(e^{-i\omega t})\|_\infty \leq 1$ to invoke the small-gain theorem in the transformed coordinates. Had it been the case that the uncertainty was bounded by one, then it would have been possible to conclude stability directly in the passivity theorem anyhow. Thus, these transformations are not directly beneficial for analysis, however, following the cue from the previous mapping results, studies [3] and [93] made it possible to design controllers that renders the passive subsystem a norm bounded one and hence allowing delay robustness to be inspected via small-gain theorem. The resulting loop is stable regardless of delay period, hence they belong to the class of methods often distinguished as "delay-independent" methods. According to the literature, these are the most common methods applied in the face of delay uncertainty.

Delay is Small-Gain

Another possibility is to utilize the simple fact that the delay operator is gain-bounded and obtain the generalized plant by pulling out the uncertainty out of the loop. Obviously, this would be a very crude characterization of the unit circle since a unit disk is used as the uncertainty instead. However, as we show later, wave variables/scattering transformations directly use this conservative formulation to model the delay in the stabilization of the loop.

A similar approach is reported in [80] using μ-synthesis. By exploiting the low frequency property of the operator $e^{-sT} - 1$ and covering with a dynamic filter, the conservatism is reduced. But the authors have omitted the uncertainty of the human and the environment. Therefore, their analysis is only valid for nominal teleoperation systems. Though, this can be extended to more general cases, we have to note that, they don't consider the human as "some impedance+state-independent force input" but as an finite-energy force input signal filtered through the human characteristics. Technically, this amounts to the common disturbance input-filtering often used in the H_∞ design problems.

2.3 Synthesis

Complementary to the analysis section, we cover a few popular controller structures among many others except the art of control engineering; manual PID tuning.

2.3.1 *Two-, Three-, and Four-Channel Control Architectures*

In the teleoperation literature, the control laws are categorized in terms of how many measurement signals are sent over to the opposite medium during the teleoperation for control. The actual controller synthesis method is often not considered in this classification. Hence the naming "n-channel control". The naming scheme can be better visualized as shown in Figure 2.12.

Position-Postion and Position-Force Controllers

The most basic control architecture among all is probably the PERR (position error) control in which the position of both the local and the remote site devices are collected by the controller and control commands are applied to both devices to minimize the position difference regardless of which device is falling behind in terms of tracking.

Assume that the local and the remote device are at rest at position $x = 0$ in the respective world coordinates. Also assume that the user moves the local device to position $x = 10\,\text{cm}$. What the control algorithm should do is to measure the position difference and force each device accordingly to minimize the error. Hence, the control law is of the form

$$\begin{pmatrix} F_l \\ F_r \end{pmatrix} = \begin{pmatrix} -1 \\ 1 \end{pmatrix} K_p(s) \begin{pmatrix} 1 & -1 \end{pmatrix} \begin{pmatrix} x_l \\ x_r \end{pmatrix}.$$

where F_r, F_l denote the control action at the local and the remote sites. $K_p(s)$ can be a constant or a SISO dynamical system or any other esoteric control law. One can perform the same with velocity signals (to comply with the passivity analysis) if available in noise-free measurements. Otherwise, a position drift is unaviodable even with integral action.

Typically, this control architecture would give a sluggish performance since there is no preference or priority in correcting the error signal on each side. Therefore, while the remote site is pulled forward to track the local device, simultaneously, the local device is pushed back with the same force. This results in a feel similar to extending a damper, only in this case, it softens up according to the position error instead of the travel velocity.

Another widely used control architecture is the so-called Position-Force Controller. In this method the first channel in the PERR control structure is replaced with the remote site force input. Hence, the local site device tracks the remote site encountered force while the remote site device tracks the position of the local site device which can be represented by the following description

$$\begin{pmatrix} F_l \\ F_r \end{pmatrix} = \begin{pmatrix} K_f(s)F_{env} \\ K(s)(x_l - x_r) \end{pmatrix}.$$

Clearly, the side-effect of PERR type control is avoided since the position and force errors are tracked independently in two seperate channels. But this brings in another tuning problem: If the position control gain dominates, the force tracking behaves aggresively in the hard contact case due to the overuse of control action to drive the remote device into the obstacle and generally results with a kickback of the local device. Conversely, a domination of the force gain results in chattering of the remote device on the obstacle due to the discontinuous nature of the force reference signal if the user touches the handle just softly enough to sustain an oscillation. Therefore, not only the gains of the individual channels are hard to tune, but also the relative magnitudes of the gains makes the tuning more tedious.

Force-Force+PERR

To increase the bandwidth and to reduce the side-effects of the aforementioned methods, a feedforward controller is added to the position-force control architecture.

$$\begin{pmatrix} F_l \\ F_r \end{pmatrix} = \begin{pmatrix} K_{f1}(s)F_{env} \\ K(s)(x_l - x_r) + K_{f2}(s)F_{hum} \end{pmatrix}.$$

Hence, this scheme is called a three-channel controller. This has been introduced in [43] and also analyzed in [91].

Lawrence Control Architecture

In [78], a general control scheme was proposed (later extended by [34, 42]). In this architecture, also the remaining channel of remote position is sent over to the

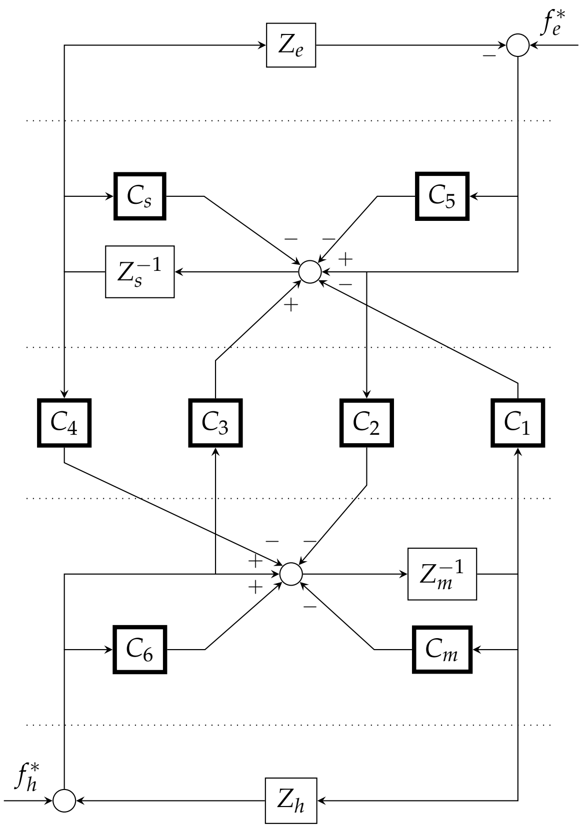


Figure 2.12: Extended Lawrence Architecture, adapted from [43]. Starred signals are the exogenous force inputs by the human/environment

local site, completing the number of measurement channels to four. The individual controller blocks and the resulting overall block diagram is shown in Figure 2.12.

Instead of a such classification, one can directly start with a MIMO control structure while keeping the control problem formulation fixed. For this purpose, let $Y_1 \subseteq \mathbb{R}^{f_1} \times \mathbb{R}^{f_2}$ denote the force measurement space, $Y_2 \subseteq \mathbb{R}^{p_1} \times \mathbb{R}^{p_2}$ denote the position measurement space harvested from arbitrary number of sensors and consider the control mapping $K : Y_1 \times Y_2 \to \mathbb{R}^{m_1} \times \mathbb{R}^{m_2}$ from the measurements to the local and remote control actions via

$$\begin{pmatrix} F_l \\ F_r \end{pmatrix} = K \begin{pmatrix} x_l \\ x_r \\ F_{hum} \\ F_{env} \end{pmatrix} := \begin{bmatrix} -C_m & C_4 & C_5 & -C_2 \\ C_1 & C_s & C_3 & -C_6 \end{bmatrix} \begin{pmatrix} x_l \\ x_r \\ F_{hum} \\ F_{env} \end{pmatrix} \tag{2.4}$$

where m_1, m_2 denote the actuation inputs with overactuated robotic manipulators in mind. The grayed entries are the control subcomponents that work on the variables sent over the network. If we recap the architectures above with this notation, they can be represented as

$$K_{PERR} = \begin{bmatrix} -k & k & 0 & 0 \\ k & -k & 0 & 0 \end{bmatrix} \begin{pmatrix} x_l \\ x_r \\ F_{hum} \\ F_{env} \end{pmatrix},$$

$$K_{PF} = \begin{bmatrix} 0 & 0 & 0 & k_f \\ k & -k & 0 & 0 \end{bmatrix} \begin{pmatrix} x_l \\ x_r \\ F_{hum} \\ F_{env} \end{pmatrix},$$

$$K_{\text{3-channel}} = \begin{bmatrix} 0 & 0 & 0 & k_{f1} \\ k & -k & 0 & k_{f2} \end{bmatrix} \begin{pmatrix} x_l \\ x_r \\ F_{hum} \\ F_{env} \end{pmatrix}$$

respectively. Each k_i represents some constant or dynamic controller. Obviously, one can generate many more architectures by populating different entries and the zero blocks.

In [44] (see also **[rajuwerg]** for a specialized treatment), the perfect transparency conditions are given for the undelayed case as the following; If $C_1, \cdots, C_6$ are not functions of Z_h and Z_e, transparency is achieved if and only if the transparency-optimized control law

- $C_1 = Z_{cs}$
- $C_2 = 1 + C_6$
- $C_3 = 1 + C_5$
- $C_4 = -Z_{cm}$

where $Z_{cs} := Z_e + C_m, Z_{cm} := Z_h + C_s$ hold for nonzero C_2, C_3.

2.3.2 *Wave Variable-Scattering Transformation Control for delays*

We have discussed the transformation from a passive interconnection to small-gain interconnection via the Möbius transformation W. However we have assumed that the interconnection did not involve any communication delays. When the delays are introduced in the loop as depicted in Figure 2.13, the transformations actually shift the stability problem from one domain to another. In other words, the transformations make the delay operators unbounded-gain as we have showed previously. Therefore, interconnection of passive and small-gain operators avoids to be handled by neither small-gain nor passivity theorems. Hence, we are left with

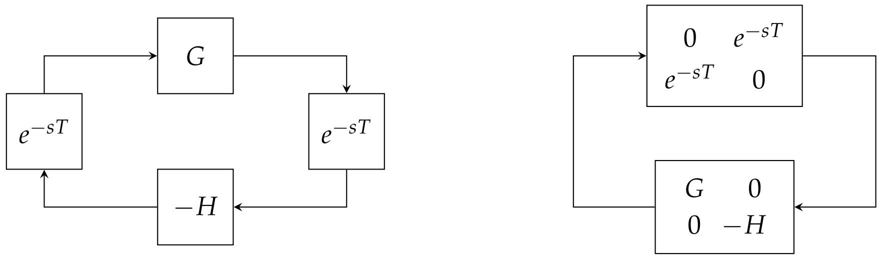


Figure 2.13: A delayed interconnection in the input/output setting and block diagram as a two block interconnection.

the only option to modify the system. This technique has dominated the literature thanks to [3, 93, 94].

Suppose we are given strictly passive LTI systems G, H interconnected as shown in Figure 2.13 on the left with communication delays. We, then, rewrite the interconnection as a two block interconnection as shown on the right for which we will use the shorthand $P - \Delta$ interconnection (delay block being the Δ). Now if the system P was strictly small-gain i.e. $\|P\|_\infty < 1$, thanks to the small-gain theorem, we would have directly conclude with stability since $\|\Delta\|_\infty = 1$, i.e.,

$$\begin{bmatrix} 0 & e^{i\omega T} \\ e^{i\omega T} & 0 \end{bmatrix} \begin{bmatrix} 0 & e^{-i\omega T} \\ e^{-i\omega T} & 0 \end{bmatrix} = I \quad \forall \omega, T$$

This fact also justifies why this methodology works regardless of the delays involved. However, P is strictly passive and thus not necessarily a unity gain-bounded operator. But we have showed how to transform such operators into norm bounded ones. This is actually the key point of the wave variable transformations. We simply use the mapping $W(P)$ and obtain

$$W(P) = (P - I)(P + 1)^{-1} = \begin{bmatrix} G - I & 0 \\ 0 & -H - I \end{bmatrix} \begin{bmatrix} G + I & 0 \\ 0 & -H + I \end{bmatrix}^{-1} \tag{2.5}$$

$$= \begin{bmatrix} W(G) & \\ & W(-H) \end{bmatrix} \tag{2.6}$$

This constitutes as a simple justification of the common “left” and “right” scattering transformation of the port terminations, leaving the delay operators in the “hybrid” structure untouched in the two port network terminology. Note that, we have only applied the mapping W to P and there is no inverse mapping to “undo” this in the loop. Technically speaking, this is not precisely a complete loop transformation since we have applied W to system P but not to the delay block Δ. Thus, the additional feedback and feedforward branches together with the $\sqrt{2}$ gains shown in (2.2) constitutes a genuine controller. In other words, the transformation block diagram is precisely achieved by the use of a feedforward/feedback control law, which can be represented by Equation (2.4). The explicit derivation of the wave variable controller entries, in terms of a MIMO controller, is given in [19]. One can also verify that the control law given in [3] can be obtained via this formulation.

It is this very reason that the motivation often found in the literature is slightly misleading. Because, we did not and also could not do any modification on the delays. Quite the contrary, we have modified our system such that we can use the small-gain theorem to conclude stability in the face of Δ. Therefore, we refrain from seeing this method as a passification of the communication channel. It is certainly possible to reflect the transformation on Δ and invoke an impedance matching argument but we think that this only complicates the presentation. Because it's the change in the control action that stabilizes the loop, and not the change in the characteristics of the delay operator or making the communication line a lossless LC line. We have to emphasize that this transformation does not guarantee stability if the original P is not strictly passive. However if any other plant $\hat{P}$ from an arbitrary class of systems X can be brought into a unity norm-bounded form with some other transformation/control law. Then we can infer another set of physical interpretations as we would have X-ified the communication channel. Thus, if we replace X with "passive" the class of systems become the passive system class and we declare that we have passified the communication channel. However, the communication line stays untouched in both cases, though the control action on the system would be different. Therefore, it is, in our opinion, better to state the changes done on the system instead in terms of control laws.

Clearly, we have introduced the same conservatism by treating Δ as a gain-bounded operator that μ-analysis approaches also utilize. Moreover, we have directly transformed the strictly passive operator to a small-gain operator. In case of a passivity excess, i.e., the mapped operator is confined only in a subregion of the unit disk, we, yet again, introduce further conservatism by using encapsulating the smaller disk with the unit disk, for which one can shift the disk to the origin and use the scaled small-gain theorem to reduce the conservatism. We should note also that, this method works for any norm-bounded linear/nonlinear Δ operator as long as the passivity structure is preserved and certainly not limited to delays (as in the passivity case, it's that conservative).

Furthermore, if one shuffles the loop equations and bring Δ to a block diagonal form while the system in turn admits an anti-diagonal structure, it's possible to formulate a μ-synthesis problem. By doing so we can recover the setup of [80]. Then, we can easily see that a wave variable control law above is in the subset of all stabilizing controllers set (due to the particular zero blocks in the controller structure). Thus, in terms of the conservatism involved, μ-synthesis with constant D-scalings ($D = I$) covers the wave variables controller design implicitly.

It has been noted the these control algorithms are prone to position drifts due to the velocity communication and different alternatives have been proposed to tackle this mismatch e.g., [18, 131]. Also there are generalizations of the scattering transformations available in the literature, e.g., [48] to exploit the degree of freedom on the mapping W using different rotation-scaling combinations for the unitary

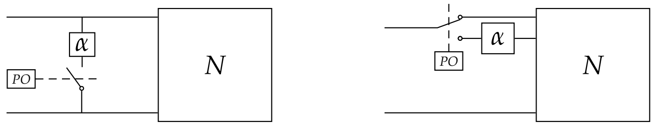


Figure 2.14: Passivity Controller (PC) implemetations.

transformation matrix and also [121] for multidimensional systems. Delay problems are also addressed in this context e.g., [17, 89, 92, 124] and references therein.

2.3.3 *Time-Domain Passivity Control*

In [41], the passivity approach is formulated in the time domain and the energy exchange is literally monitored and regulated. An initial version of this idea can also be found in [131]. The basic idea is to see whether at any port energy is generated, using a "passivity observer" (PO): for an N-port network the observed total energy is given by

$$E_{obsv}(n) = \sum_{k=0}^{n} \Delta T_k (F(k)^T V(k))$$

where ΔT_k is the sampling period at each step with nonuniform sampling in mind. If $E_{obsv}(n)$ is greater than or equal to zero then the energy is dissipated by the network, conversely if it is negative at some k, then the network has generated energy equal to the amount of $-E_{obsv}(n)$. Note that this is a cumulative term and it is not implied that the energy is generated in the last step analogous to the integral-action control. Also, it has been shown that observing the energy flow only at the open-ports is sufficient to monitor the total "net" energy flow which is analogous to the observability concept in the linear control theory.

The "Passivity Control" (PC) is implemented on top of this observer architecture as a virtual dissipative element. It relies on the passivity observer and if the energy generation is detected a dissipative element is introduced. The practical implementation is very similar to a safety relay circuit, i.e., it's only active when some relay switch is triggered. Depending on the causality (following the our analogy, as a current sensing or a voltage sensing relay), the PC can be implemented in series or parallel to the port.

This concept is then generalized to two-ports in [110, 111]; also results regarding the delay problem in the Time Domain Passivity Control context can be found in [109]. Since the essential architecture is a PI controller, it also suffers from the same problems that integral-action controllers suffer such as, wind-up and integrator reset etc. Some of these problems are addressed in [68].

2.3.4 *Others*

We have shown that most of the proposed methods in the literature use passivity or small-gain theorems and the involved mathematical operators are often indistinguishable from any other physical setup that is not a teleoperation system. It's our belief that, without any further refinements, all the above methods can be shown to be, essentially, equivalent stability characterizations as far as practical implications are concerned.

There are other approaches such as Energy Bounding Algorithm (EBA), [66, 113], sliding mode control, [14, 99], reset control, [126], model predictive control [7, 114] and many more which we will omit here. These studies also involve model-based control techniques with varying degree of dependence on the model.

The proposed methods often avoid the discussion on how to tune the PID controllers for the local, remote, and the communication line. It's as if those details are easy to handle and the attention is shifted to the n-channel architecture. We have no evidence supporting this in the control design papers. Alternatively, very conservative upper and lower bounds are given on the parameters of individual controllers and, therefore, the underlying control architecture is extremely simple since otherwise the proposed methods suffer from exceeding complexity in the derivations. This is yet another reason for why we have chosen the IQC framework for robustness analysis and model-based control path in the first place.

It's our humble opinion, however, that a "one-size-fits-for-all" design toward operator- and task-aware control laws without dedicated modeling and/or classification, seems very unlikely to produce a generally applicable results with high-performance guarantees. Nevertheless, robust control at least addresses the conservatism reduction in a systematic way, if there is no other way to model the teleoperation systems. Moreover, Linear Parameter Varying controllers are to the best of our knowledge, not yet pursued to the extent the theory allows for.

We cannot claim that we have surveyed the literature in this brief and biased survey in a comprehensive manner. The omission, as we have mentioned before, is a pragmatic choice. Though a body of research is left out (in particular most of the nonlinear methods), the covered part also constitutes a significant volume and in the next chapter they are detailed further. However, we have to note that, most nonlinear methods are the counterparts of the linear passivity theorem methods given here and they do not introduce a different look on the modeling and analysis problem per se. Thus, the motivation holds for some of those nonlinear cases.

Moreover, the number of studies reported in the literature is rapidly increasing and quite difficult to follow even under the guidance of at least two survey papers published recently [55, 100]. We have to point out that there is still no consensus on the simplest conventions and the results are often very challenging to differentiate. Hence, there is a great need to have authoritative and comprehensive sources since the survey papers above don't go into details. As a closing remark, we would like refer to the outstanding survey of [69] which provides also a comprehensive outlook to the teleoperation literature in a relatively detailed fashion up to 2006. It should give the reader a good idea how involved and, as a subjective note, unnecessarily complicated the bilateral teleoperation literature is.

CHAPTER 3

Performance Objectives

Bilateral teleoperation problem is probably one of the most difficult problems in the control field due to its subjective nature involving the human comfort and liking. However, to put it bluntly, the experts are not helping either. In other words, most of the "good performance" motivations come out of modeling first-principles but not out of the user experience. Some literature argue that since most of the tools we utilize are (almost-)lossless, say, a screwdriver or even a simple stick, it's natural to seek for a passive bilateral teleoperation system (though if we insist on this analogy, a lossless system should be sought after) that ideally behaves like a rigid transmission mechanism. In the work of Daniel and McAree [26], it has been strongly recommended that one should focus completely on the underlying physics and in fact the authors boldly established an essential limit to what can be achieved by bilateral teleoperation:

> Although our motivation comes from the problem of building teleoperators to perform tasks of this sort, there is much here that we feel is common to all teleoperation. The performance of every force-reflecting system is ultimately governed by dynamic interactions between the master, the slave, the human operator, and the environment. For some applications different effects may dominate; e.g., transmission delays limit what can be achieved in space applications of telerobotics ([...]). But one can never achieve better performance than that determined by rudimentary physics. For this reason, we call the limits of performance examined here *fundamental limits of performance*. ([26])

This statement summarizes perfectly what the contemporary bilateral teleoperation literature promotes. The reason why we strongly disagree with this statement should be evident at the end of this chapter and later in **??**. Still, to provide a contextual introduction to the discussion, we first remind that the underlying physics does not only consist of two distant robots interacting with their corresponding surroundings. The actual physiscs involve the human liking and that gives us freedom to display whatever is considered to be "cool, nice, crisp, real, helpful" by the human operator. It doesn't matter if we are off by 10 N or some other reflected quantity is not in accordance with the actual measurement; as long as the human operator is happy with the result in terms of immersion and touch sensation, we are done. There is nothing fundamental in terms of technological limits of performance and there is nothing wrong with approximating (or even altering) the reality to achieve the required technology. In fact in our opinion, this is an instance of the common academic practice; obfuscation by purism.

In order to justify such fundamental limitations, we have two missing ingredients in [26]; the required precise tools that do not bring in any lossy simplifications and the exact mechanism described completely by the actual physics. Unfortunately, their analysis rely completely on LTI root loci tools and human preference is openly skipped. Therefore their results can at best be the fundamental limitations of what the literature claims the bilateral teleoperation is to be.

In general, there is no established consensus on what makes a teleoperation system "good". Quite the contrary, this question is openly and unambiguously avoided in some well-acknowledged articles. Instead some possibilities are proposed and rigorously pursued to the end without actually validating if these possibilities reflect our intention. Therefore, the conclusions that these studies arrive at are the implications of their initial hypotheses. However, the studies that follow these publications do not take this crucial detail into account and proceed as if these performance objectives are indeed the ultimate goals. We have to claim that the motivation of most of the studies given in the literature erroneously put emphasis on performance objectives that are at best suggestions and often questionable.

On the other hand, there is a different school that focuses only on stability of the teleoperation system in the face of human, environment, communication line, quantization and many more uncertainty/perturbation sources. Especially some nonlinear control studies do not even bother to define performance criteria. This view simply regards the human/environment as perturbations for our precious robotic systems and neglects the "*reason d'etre*" of the very problem that is under consideration. In our opinion, operator perception is the indispensable performance objective and can not be overlooked. But it is also very difficult to quantify. More importantly, it is beyond the scope and expertise of control theory (though with certain overlap) to find the relevant objectives. Other experts of the related fields need to contribute from a technological point of view in contrast with a pure physiological point of view and, in fact, should guide the control theorists and practitioners towards the relevant issues. This lack of performance specifications is the main reason why we have left out a considerable body of research out in our literature survey.

We strongly believe that the contemporary bilateral teleoperation control results, including this thesis, cannot and thus should not claim a comprehensive understanding of a good and useful bilateral teleoperation system. Because we just don't know, yet.

3.1 Types of Performance

In terms of the quality of the force-feedback, there are a few leading choices of methodological performance definitions. The widely accepted so-called "transparency" stems from the ideal case of lossless, undistorted exact replica of the remote side physics at the local site. Hence the ultimate goal is selected to be faithfully representing the remote site motion and allowing the user intervene just as good as s/he is operating directly at the remote site. Let us provide some background how transparency is often provided and/or motivated. We choose to follow [49] for no particular reason other than the manuscript being the introduction/survey chapter of a recent collection of *Advances in Telerobotics* (but alternatively [29, 40, 132] and many others can be followed too); first we again recognize the motivation for modeling via n-ports

> For the analysis and control synthesis the modeling of the bilateral teleoperation system as interconnection of two-ports, [...], is convenient.

Then, the intuitive definition of transparency is provided. We draw the attention to the transition from the informal description to the technical formulation of transparency.

> Transparency of the telerobotic system is the major goal in bilateral control architecture design.
>
> **Definition** (Transparency)**.** *The telerobotic system is transparent if the human operator feels as if directly interacting with the (remote) task [10]*[1]
>
> Formally, transparency is achieved if the transmitted and the environment impedances match [11][2] as also indicated above
>
> $$Z_t = Z_e$$
>
> or alternatively if HSI (master) and teleoperator (slave) movements are equal and the force displayed to the human operator is exactly the reaction force from the environment [12][3]
>
> $$x_h = x_e \text{ and } f_h = f_e$$
>
> Transparency in this sense is in practice not achievable as the device dynamics comprising inertia and friction cannot completely cancelled by control. Communication effects, especially time delay, severely degrade the achievable transparency. The development of quantitative measures is part of the transparency analysis...

This transition is practically in all documents which treat transparency as the major goal in the literature. In particular human *feel* suddenly disappears from the picture and only the physics between the tips of robotic devices are considered. We have no source in the literature that avoids or at least mentions this interesting omission. Let us first give a detailed discussion of transparency to be able to clarify what is exactly omitted since there are a few layers of omission in such arguments.

[1] Reference [106] of this thesis.
[2] Reference [78] of this thesis.
[3] Reference [132] of this thesis.

3.1.1 *Transparency*

Typically, we classify materials as opaque or transparent based on how good we can see through an item made up of that particular material. If we simply replace the act of seeing the other side with touching the remote location, the less distorted a system transmits the remote motion to the local site, the more transparent the system is. Hence the term *transparency*. This is defined in [78, 132] independently. In fact, the notion of transparency is of three ideal response definitions in [132]. Resuming the notation from Chapter 2, a perfect or ideal transparent 2-port network admits the hybrid matrix

$$\begin{pmatrix} v_{hum} \\ f_{hum} \end{pmatrix} = \begin{pmatrix} 0 & I \\ -I & 0 \end{pmatrix} \begin{pmatrix} f_{env} \\ v_{env} \end{pmatrix}$$

If we wish to translate this into a control theoretical performance objective, we have essentially two options. First option is minimizing the difference between the measured force/velocity signals of the actual system and the force/velocity signals of the hypothetical perfectly transparent system would have exhibited in that particular configuration. Second option is to make our system behave like an ideal transparent system as much as possible.

Let N denote the overall controlled teleoperation system model with the controller K, i.e. $N(K)$. Then we can define a performance index

$$\min_K \left\| \begin{pmatrix} f_{hum} - F_r \\ f_{env} - F_l \\ x_{loc} - x_{rem} \\ \vdots \end{pmatrix} \right\|$$

for all the admissible signals of time in some suitable normed space that we wish to consider. Alternatively, using a suitable system norm the problem becomes

$$\min_K \left\| N(K) - \begin{pmatrix} 0 & I \\ -I & 0 \end{pmatrix} \right\|.$$

Notice that selection of the suitable norm is far from trivial and we might even need an amalgam of different norms to bound both the energy and the maximum value of the error signals. However, this choice is understandably limited to the tools that we have for analysis and synthesis. This choice of enforcing an ideal teleoperation is obviously intuitive and agrees with the underlying physics if only we remove the human perception out of the loop. Thus, one could only argue that the global minimizer of these optimization problems would lead to the best teleoperation system unless we include the operator's opinion. However, there are two additional implicit assumptions made here. On one hand, it is assumed that there is a partial ordering, in other words, if K_1 has the cost c_1 and K_2 has the cost c_2 with $c_1 < c_2$ then this implies that K_1 is better than K_2 which is not necessarily true, or better, it might hold only for some particular K's. In general no such ordering can be expected from this performance index. Moreover, it's not easy to search for such K. As we have observed in the literature, almost every transparency optimized control method selects the full performance first hence assuming the global minimizer and then tries to stabilize the system in the face of those performance specifications. Obviously after adding dampers or other dissipative elements the system is no longer a transparent teleoperation system and moreover we don't have a way to measure how much we are off from the initial perfectly transparent system since we only know what is ideal.

On the other hand, we do not have a metric for how much we need to get close to the ideal matrix. Let us first quote three very important questions posed by Lawrence in his well-known paper [78];

> In practice, perfectly transparent teleoperation will not be possible. So it makes sense to ask the following questions:
>
> - What degree of transparency is necessary to accomplish a given set of teleoperation tasks?
> - What degree of transparency is possible?
> - What are suitable teleoperator architectures and control laws for achieving necessary or optimal transparency?
>
> We focus on the second two questions in this paper. Instead of evaluating the performance of a specific teleoperation architecture, as in [2], we seek to understand the fundamental limits of performance and design trade-offs of bilateral teleoperation in general, without the constraints of a preconceived architecture. ([78])

Lawrence then invokes the passivity assumption of the end terminations and hence the passivity theorem is utilized to arrive at structural properties of the controller K. Evidently, this allows for the back-substitution of the controller entries and solution for the ideal case. Then the resulting controller is denoted with "*Transparency Optimized Controller*". In control theoretical terminology, this amounts to a cross-coupling control action where the bilateral dynamical differences are canceled out and then SISO control channels are tuned to maximum performance bound to the stability constraints.

Even if we accept it to be the distinguishing performance criterion, we have to emphasize that we have not touched the most important question, that is the first of the three, rather we hope to achieve the required transparency levels just enough to fool the user. After two decades, this point is simply discarded and many studies in the literature somewhat treats the conclusions of Lawrence in a different context than what has been given by Lawrence. As is for the case for Hogan's paper on passivity, Lawrence never claims that this is a definite performance measure. Instead he clearly shows the implications that follow from such assumptions.

Finally, there are interesting studies inline with our claims about irrelevance of the remote media recreation in bilateral teleoperation problem. For example, [9, 65, 128] and a few other studies report that there is a saturation effect on how much realism that can be projected to the user. In other words, there is an inherent bandwidth limitation for the realism increase such that beyond a certain band of frequency, the transparency does not increase significantly, possibly unless backed up by tactile feedback. Even further, in the case of shared control applications, it might happen that transparency is not needed at all.

3.1.2 *Z-width*

In [25], the performance of a haptic device is related to the dynamic range of impedances (hence the name Z) that the device can display to the user. In this context we have two extremes; on one hand we have purely the local device impedance for the free-air motion and on the other hand we have the maximally stiff local device for the rigid and immobile obstacle collision. Let Z_f, Z_c denote these two distinct cases. Then the more pronounced the difference between these impedances, the more capable the teleoperation system can reflect various impedances inbetween. Thus, we implicitly assume that the rigid contact case and the free-air case are the extreme points of the uncertainty set and testing for these two cases are sufficient to conclude that any impedance on the path from Z_f to Z_c is a valid impedance that can be displayed by the device. This in turn implies that there is an ordering in the uncertainty set from "big" to "small" etc. and moreover the destabilizing uncertainty is at the boundary of the set such that these two extreme cases can vouch for stability over the whole possible environments. We are not convinced that this should be the case for all possible environment scenarios. A particular subset of second-order mass-spring-damper models of environments can be shown to be compatible with this claim if passivity theorem is used. However, when combined with other uncertain blocks in the loop we do not see how the argument follows. Note that it is well-known in the robust control literature that a destabilizing uncertainty need not to be living on the boundary of the uncertainty set. Therefore, either by gridding the uncertainty set and testing the stability conditions on a large number of points or by a specific relaxation on the constraints conditions should be translated to finitely many (and computationally tractable) number of points stability is guaranteed over the whole uncertainty set.

Similar to what Lawrence has given, the authors also include a clear statement of purpose:

> This paper will not address the psychophysics of what makes a virtual wall "feel good" except to say that one important factor seems to be dynamic range. An excellent article on this topic has recently been written by Rosenberg and Adelstein [11][4]. We will present instead some

[4] Reference [108] of this thesis.

> of our findings, both theoretical and experimental, concerning achievable dynamic range. In short, we will address the question of how to build a haptic interface capable of exhibiting a wide range of mechanical impedances while preserving a robust stability property. ([25])

Under these assumptions, via defining a functional to measure the distance between Z_f and Z_c, we can assess the performance of different bilateral teleoperation devices. In [20], this so-called Z-width is defined as

$$Z_{\text{width}} = \int_{\omega_0}^{\omega_1} \Big|\log|Z_c(i\omega)| - \log|Z_f(i\omega)|\Big| d\omega \tag{3.1}$$

or alternatively, a simulation/experiment-based method can be utilized as in [127].

Note that (3.1) does not appear in the original paper [25] but proposed in [20, 100] though we can see neither the reasoning behind this expression nor how it constitutes a comparative quantity. In both [20, 25] no additional information is provided except some general rules of thumb about device damping and other related issues.

It should be noted that the differences at each frequency are lumped into one scalar number and moreover, the impedance gain curves can cross each other (see [20]) and might lead to an overly optimistic result. Similarly, resonance peaks and zeros of the involved impedances can be smeared out if we solely rely on this functional.

Since Z_f and Z_c are functions of the environment impedance, these curves can be obtained for one particular environment at a time. This also holds for the derivation of [78]. In [20], the difference is evaluated for more than one environment and then averaged out i.e. let $Z_{act}(Z_e)$ be the impedance displayed to the user in order to render Z_e on the local site. Then, for a particular controller, average Z-error to each candidate Z_e is given by

$$Z_{avgerr} = \frac{1}{n}\sum_{j=1}^{n}\left[\frac{1}{\omega_{1j}-\omega_{0j}}\int_{\omega_0}^{\omega_1} \left|\log|(Z_{act}(Z_{ej}))(i\omega)| - \log|Z_{ej}(i\omega)|\right| d\omega.\right] \tag{3.2}$$

This cost function is denoted by "*Transparency Error*" or "*Fidelity*". We refer to [127] for a more detailed discussion.

3.1.3 *Fidelity*

In [15], a variant of a transparency error is proposed to assess the performance. In this context, the emphasis is on the variation of the environment impedance and the resulting effect on the displayed impedance. Also the motivation is focused on the surgical procedures via bilateral teleoperation. If, for example, the remote device slides over some tissue that involves a tumor or any other irregularity that would be felt had the same motion performed directly by the surgeon, the better the nuances transmitted, the higher the fidelity. This performance objective, in a sense, enforces the high frequency content of the information (closer to tactile bandwidth). It has been noted that the Just Noticable Difference (JND) of [14,25] % for distinguishing relative compliance of similar surfaces goes under 1 % for rapid compliance variation detection while, say, scanning a surface [28]. Similar to the definitions given for transparency, the change of the displayed impedance $Z_{disp}(Z_e)$ with respect to the change in the environment Z_e can obtained via a straightforward calculation.

Consider again the system interconnection as depicted in Figure 2.2b. Given the scalar complex LTI uncertainty block Δ and the LTI plant $G \in \mathcal{RH}_\infty^{2\times 2}$. The upper LFT interconnection of $\Delta - G$ is given by,

$$P = G_{22} + G_{21}\Delta(I - G_{11}\Delta)^{-1}G_{12}$$

Here P denotes the impedance seen by the operator (the environment), G denotes the teleoperation system and Δ being the environment (operator) impedance. Now, under the well-posedness assumption, define the derivative operation with respect to change in Δ

$$\frac{d}{d\Delta}P = \frac{G_{21}G_{12}}{(I - G_{11}\Delta)^2}$$

then, though not pursued in [15] and left as a complication, this can, in turn, be rewritten as an LFT again;

$$\begin{pmatrix} q_1 \\ q_2 \\ z \end{pmatrix} = \begin{pmatrix} 2 & 1 \\ 1 & 0 \\ 2G_{12}G_{21} & 2G_{12}G_{21} \end{pmatrix} \begin{pmatrix} G_{11} & 0 & 0 \\ 0 & -G_{11} & 1 \end{pmatrix} \begin{pmatrix} p_1 \\ p_2 \\ w \end{pmatrix}$$

and

$$\begin{pmatrix} p_1 \\ p_2 \end{pmatrix} = \begin{pmatrix} \Delta & 0 \\ 0 & \Delta \end{pmatrix} \begin{pmatrix} q_1 \\ q_2 \end{pmatrix}.$$

Note that the matrix case follows a similar but more involved computation. Moreover one can recognize the familiar plant-uncertainty representation clearer without any complication.

Consequently, the authors define a transparency-like performance objective using a rather subtle choice of system 2-norms.

Definition (System 2-norm)**.** *Let G be a stable LTI system with transfer matrix G(s). Then*

$$\|G\|_2^2 := \int_{-\infty}^{\infty} \operatorname{tr}(G^*(i\omega)G(i\omega))d\omega$$

The measure of fidelity is defined as the norm

$$\left\| W_s \frac{dP}{d\Delta}\bigg|_{\Delta_{enom}} \right\|_2$$

where W_s is a typically low-pass type weighting function to emphasize the frequency band of interest. Therefore the synthesis problem is to find the optimizer, controller K to the problem

$$\sup_{\substack{\text{Stability}\\ \text{Other Constraints}}} \inf_{\Delta_{ei}\in\mathbf{\Delta_e}} \left\| W_s \left.\frac{dP}{d\Delta}\right|_{\Delta_{ei}} \right\|_2$$

where Δ_{ei} are the worst case environments that are of interest.

There are a few interpretations of this norm in the literature, mainly, the deterministic "area under the Bode Plot" interpretation i.e. energy of the impulse response for scalar case, and the stochastic "steady-state white-noise-input response". We are under the impression that the authors argue in the line of the former interpretation with a similar reasoning given in the Z-width discussion via an area computation.

Designing a robust controller while minimizing the $\mathcal{H}_2$ norm of an uncertain system in the face of a predefined uncertainty set i.e. "Robust $\mathcal{H}_2$ Synthesis" problem has already recevied a lot of attention and the results can be found in the literature, e.g., [30]. Hence, the problem definition in [15] is in fact tractable. However, it's not clear to us why we choose the system 2-norm for the performance cost. Additionally, the infimum needs to be computed in the face of a set of infinitely many points hence an appropriate relaxation is required. This point is also not given though a gridding approach seems to be utilized in the numerical optimization procedure described in the paper.

It is also not clear in which case we should utilize this performance objective. The initial difficulty is that all the involved operators are LTI hence there is no time variation involved. The test reads as; *we select an arbitrary element in the predefined uncertainty set, say Δ_e, and evaluate the derivative at Δ_e. Hence, in some ϵ- neighborhood of $\Delta_e \in \mathbf{\Delta_e}$ we can see the change in P*. Thus, if the environment is slightly off from our nominal guess, this tells us how much fidelity measure would change. But the environment is still assumed to be LTI.

Note that, this does not imply that time-variations are taken into account. Suppose a particular admissible trajectory $\hat{\Delta}_e(t)$ in time is given such that $\hat{\Delta}_e(t_1) = \Delta_e$ i.e. its time-frozen LTI copy coincides with the particular nominal environment model Δ_e and at some time instant t_2, it coincides with another LTI model $\mathring{\Delta}_e$ that is within some ϵ-neighborhood of Δ_e. Even if we achieve very good fidelity properties evaluated at each Δ_e and a sequence of LTI model elements each being in the small neighborhood of the other, this does not guarantee that we would have good fidelity for the trajectory $\hat{\Delta}_e$. Actually, it might be more desirable to have low fidelity since drastic changes in the performance with respect to LTI uncertainties might confuse the user.

3.2 Closing Remarks and Discussion

There are a few other performance criteria reported in the literature. Consider the definition of the impedance seen by the operator P above. In [59, 62], this term is divided into two individual terms, denoted by "reproducibility" and "operationality". The idea is similar to a sensitivity/complementary sensitivity function definitions.

In [132], also an ideal response is also partitioned into two parts and denoted by "index of maneuverability" and, in essence, is similar to what is given above, hence omitted.

We refer to the survey papers [55, 100] for a general treatment and [69, 104] and references therein for a more detailed overview about many variations in the literature.

In summary, there are no general perfomance criteria that can lead to a dedicated control design procedure. The aforementioned performance objectives always start from the direct manipulation case and assume a distance between the interacting bodies. Then the implications of such hypotheses are pursued and some results are obtained. It might very well happen that all or none of those conclusions are correct. Put better, these studies always try to remedy the distortion caused by the split of two interacting bodies i.e. teleoperation. Thus, the goal becomes too ambitious at the outset. Similar to the delay phenomenon, there is not much we can do about the distortion within the laws of physics. In fact, even the slightest delay can destabilize the system which is again an indicator of the fragility of the problem formulation. Thus, we can speculate that by doing so, we create a stability problem that we should not have had in the first place. Moreover, as we have mentioned in the introduction, the problem is exclusively about human perception and is not related to the reconstruction of the remote scene. As long as we can "fool" the user for the sake of efficiency and operational comfort, we are done.

Because we fail to provide an alternative performance criterion, we are forced to use a particular analogy from the audio technology, to express more clearly what we intend to emphasize.

When it comes to the faithful reconstruction of the recorded audio, contemporary high-end sound systems offer great fidelity, hence the name hi-fi systems[5]. There has been such a great success that now listeners and component manufacturers are striving for a full audio immersion i.e. listening to a recording that feels like actually sitting in the concert hall or venue. However, very similar to the transparency discussion in bilateral teleoperation, there is a fundamental obstacle in rendering a live performance sound with the recorded version of it. Following quote is from [5]:

> "What on earth can be the readily identifiable difference", I wrote in 1995, "between the sound of a loudspeaker producing the live sound of an electric guitar and that same loudspeaker reproducing the recorded sound of an electric guitar?" I went on to conjecture that the act of recording inevitably diminishes the dynamic range of the real thing. The in-band phase shift from the inevitable cascade of high-pass filters that the signal encounters on its passage from recording microphone to playback loudspeakers smears the transients that, live, the listener perceives in

[5]The term was coined way before the systems become truly hi-fi if compared to today's systems

> all their spiky glory. And as a high-pass filter is never encountered with live acoustic music, that's where the essential difference must lie, I concluded, quoting Kalman Rubinson (...) that "Something in Nature abhors a capacitor."
>
> But two more recent experiences suggest that there must be more to the difference than the presence of unnatural high-pass filters. (...)

The author goes on to list the involved hardware, the signal chain, and other relevant details about the mic set-up at both events. In the first event, a performer plays a piece through the listed hardware and is simultaneously recorded by the author. Then the recorded version of the performance is played back to the same audience from the same hardware. In the second event, a nontrivial analog/ digital hybrid device, which supposedly replicates a grand piano via sophisticated mechanisms, used to generate the sound. In both events, it has been noted that though the reproduction quality was quite impressive for the audience, a certain liveness was missing.

> So these days, I'm starting to feel that it is something that is never captured by recordings at all that ultimately defines the difference between live and recorded sound. (...)[the described systems] succeeded in every sonic parameter but one: the intensity of the original sound. Intensity, defined as the sound power per unit area of the radiating surface, is the reason why, even if you could equalize a note played on a flute to have the same spectrum as the note played on a piano at the same sound pressure level, it will still sound different.
>
> Ultimately, therefore, it is perhaps best to just accept that live music and recorded music are two different phenomena. (...) Eisenberg's thesis[6] is that any attempt to capture the sound of an original event is doomed to failure, and that stripping a concert from its cultural context by recording only the audio bestows a sterility on the result from which it cannot escape. The recording engineer may be able to pin the butterfly to the disc, but it sure doesn't fly any more.(...)
>
> In Eisenberg's words, "In the great majority of cases, there is no original musical event that a record records or reproduces. Instead, each playing of a given record is an instance of something timeless. The original musical event never occurred; it exists, if it exists anywhere, outside history."

Obviously, these are all subjective opinions rather than rigorous scientific propositions though the first anecdote can be considered as a user experience study. However, we have to remind that the audio technology is tremendously advanced if

[6] See [33]

compared to haptics and teleoperation. In fact, the comparison is not fair in the sense that bilateral teleoperation is not a true technology yet but rather in its infancy. Still, after decades of improvements, the sound systems are not capable of producing a live sound, real enough to make the listener immerse into, though come impressively close. Not to mention that audio technology is even a unilateral process. Nevertheless, the performance objective studies that we have enumerated a few above claim to compete at the level of hi-fi systems which is simply too ambitious. The reader should also keep in mind that the sound technology is unilateral and there is no interaction with the loudspeaker though still lacking the sufficient realism.

Coming back to our discussion, in the light of our analogy, we think that the bilateral teleoperation literature is focused on finding the system that can deliver the "live sound" rather than a high quality "playback". This holistic search is certainly relevant to the field but it cannot serve as the justification for being a driver of technological advances reported in the literature. Task-dependence is already emphasized in many studies as an item of importance and a too general performance criterion would be very unlikely to serve as a general guideline. Though, we acknowledge the motivation behind the holistic approach and a truly transparent device might be the ideal, we also believe that the timing and the feasibility of this approach needs to be modified. The immediate engineering problems such as the communication delays and other contemporary technological problems are the strong indicators of the fact that such a goal cannot be tackled prematurely. We cannot overemphasize the key issue; even the undelayed case remains unresolved let alone (time-varying or constant) delayed case.

Again from our analogy, it took decades for the hi-fi systems to reach to the current level to claim that a search for the live sound is justified. The sound reconstruction task is divided into components such as amplifiers, pre-amplifiers, direct digital-to-analog converters etc. for the signal conditioning and similarly the sound regeneration is also divided into active-passive loudspeakers with having dedicated single or multiple tweeters, sub-woofers etc. Only then the community is convinced that the hardware is not the problem[7]. Similarly, TVs and other futuristic vision technologies are following the same trend for the ultimate vision quality. However, if compared with these, bilateral teleoperation definitions are nothing but academic stability problem exercises. Moreover, as we show in the next chapter, these problems are, whether linear or nonlinear, no different than the mainstream control problems in disguise. Therefore, we can not yet argue about a dedicated stability and a performance problem for bilateral teleoperation.

This is the reason why we have chosen a significantly advanced methodology, again from mainstream control theory, and applied to the bilateral teleoperation problem. This does not imply that we have offered a valid alternative, in fact, quite to the contrary, our goal is to make it obvious that the studies so far can be subsumed

[7] We also have to state that there is an additional compulsive habit of overemphasizing the component quality such as the transmission cables etc. Hence, we can observe a trend among hi-fi enthusiasts of picking up artifacts that are impossible to be audible or simply do not exist.

into a general and widely used methodology and there is no benefit of the current specialization of the field. However, we have also shown that if the problem is in fact a special case of a general control problem there is no need to use the outdated versions of the techniques proposed in the control literature while important advances are reported in the literature in the past two decades over the plain small-gain/passivity theorem-based results.

A search over the number of studies in the literature published in the 2000's to date with "bilateral teleoperation" and "delay" as keywords gives hundreds of results. Yet we have no clear understanding of why these devices are unstable. We can pinpoint different effects depending on whether we look at it from an energy exchange/passivity point of view or from sensitivity function-based analysis. But this does not help us to prioritize certain design aspects of a high-performance system and unfortunately we have to assume a few questionable hypotheses along the way. It's very difficult to follow the train-of-thought often given in the literature as we first define the ultimate performance of a teleoperation system then we openly accept the fact that this is not achievable, however, we, in turn, do not modify our performance criteria and then completely neglect the issue. Finally we convert the problem into a stability of some interconnected devices with a great uncertainty associated with them and then, in the majority of the cases inject damping to the hardware which deteriorates not only the relative performance but usability of the device as a whole. Specific to the problem at hand, having a stable but poor-performing bilateral teleoperation has less functionality than that of a unilateral teleoperation as the added-value of robotic manipulators are wasted with the inclusion of damping.

After using the audio analogy extensively, let us finish the alternative suggestions with the same analogy. As we have briefly mentioned the hi-fi loudspeakers involve different dedicated components for different frequency bands such as tweeters for high-frequency band, sub/woofers for the low frequency bands and occasionally mid-range speakers etc. with individual drivers. Even though different components are utilized, the resulting harmony of these components leads to a very satisfactory listening experience if compared to generic single driver loudspeakers. Now, obviously somatosensory system already involves such sensors which are reported to be responsible for different frequency bands (see Appendix B). Hence, this already gives us a direct cue for separating the motion into different categories in terms of the frequency/amplitude content. We do not have a working methodology yet however we would like to include our reasoning here for comparison.

There has been quite a number of studies published on combining the tactile feedback with kinesthetic feedback such as [60, 67, 75, 84, 97] among many others and references therein. In many of these reports it has been clearly shown that combining these modalities lead to substantial increase in human perception about the unstructured environment. Not only the motion but also temperature can be transmitted via the tactile thermal actuators. Hence, different overloading of the vibrational patterns can also be obtained. We have to underline that the studies mentioned above do not necessarily promote our reasoning for the control design but rather superimposing tactile and kinesthetic perception simultaneously. However, there is no apparent obstacle to use the same hardware for cooperative kinesthetic profiling.

Therefore, from a control design perspective this gives rise to a completely different type of performance objective that has no relation with the immediate transparency requirements. In other words, the performance of the device is now comprised of the individual excitation of the required human receptors. And this is inline with what we have touched in the introduction of this thesis. To the critical reader this might look like we are shifting the difficulties of the control design to the hardware design since the required devices are indeed nontrivial. We would argue that it is not the case. The required hardware already exists but used in a different context. We have performed preliminary signal processing studies and there is no significant result that can be reported here. Nevertheless, to finalize this discussion, we can speculate about the links to a plausible solution along these lines.

The immediate possibilities are to separate either the amplitude or the frequency content of the force signal for playback. In the frequency case, instead of a "*physics*" matching goal, we instead encode the force signal to be similar to an audio signal. Then, the bilateral teleoperation system goal is to playback the measured force pattern with different components simultaneously. This has been pursued for prerecorded signals in [73] within the concept of "Event-based" haptics. The authors do not use measured signals but material contact signals from a contact-bank or look-up table but an increase of perception quality is noted. If we can achieve this separation, we have the option to separate the bandwidth of different components and hence making the performance specifications much more relaxed if compared to "one device/all frequencies" strategy. Moreover, the high frequency contact information can be shifted to the "tweeter" of the device and this makes the low frequency force playback much easier. The low-bandwidth transmission is already well-studied and within reach of the current technology. Hence, a standalone high frequency action can be added on top of the perception which would otherwise lead to a deteriorated performance if pursued with the same device. A hard contact can still be displayed with a relatively compliant "sub/woofer" and an agile stiff tweeter. Note that we are good at capturing the relative changes but not very good at perceiving the low end of the spectrum (see Section 3.1.3). Moreover, a stiff wall can possibly be rendered up to the perception threshold via it's Fourier components in other words, a hard contact perception might be achieved with a combination of mid-high frequency vibrations contingent upon the task requirements. The force signal can be transmitted and decomposed into frequency band at the local site or directly decomposed and sent over different channels with different line. This might even encapsulate the Model-mediation-like fast/slow bus discrimination without the need of recreating a proxy virtual environment update (See e.g. [86]). Moreover, this solution already embodies an inherent robustness to packet losses and similar artifacts as we have no obligation to match the physics any more. We conjecture that this would not jeopardize the stability but will make the sensation only deteriorate as we would expect from a noisy telephone conversation. As a bonus property, transmitting only the low-frequency device motion, the high-frequency content of the human input is filtered without any additional phase lag which can be beneficial for avoiding hand tremor of the surgeon etc.

It can be argued whether this would lead to a faithful representation of the remote location and we can directly see that the answer is no. However, we are trying to remove precisely that requirement and put a device-dependent varying degree of realism instead of working for stability and neglecting performance.

Without any further evidence, there is not much we can extrapolate hence we will leave this discussion to future work. Our main focus is on incorporating wavelet decomposition in particular with respect to Haar bases for encoding/decoding the contact signals. In what follows we will instead use a typical force error/position error minimization based control design and show that at least we can achieve good robustness properties for a large class of uncertainties due to human/environment dynamics with relatively high performance.

CHAPTER 4

Conclusions

In the light of all the arguments presented so far, we believe that we have clarified the underlying discrepancy between the actual bilateral teleoperation problem and how academic literature handles it. Moreover, we have provided a competitive alternative method that led to a high degree of realism experimentally. Therefore, we can safely claim that many technical problems reported in the literature are methodological and can be solved efficiently via careful modeling and robust control design phases without invoking questionable assumptions a priori. However, this claim does not reach out to the real solution of the bilateral teleoperation problem. Put better, we only claim that we have provided the solution for the simplified version of the problem. The actual question of *What makes this device good?* or even the harder *How can we improve the device?* are completely open. Unfortunately, we believe that clarifying this fact is a contribution.

Nevertheless, an important property of the method proposed here is that it provides consistent performance over different motion profiles and does not suffer from the artifacts of the method we have utilized. Moreover, we do not alter the hardware specifications by introducing virtual dissipation elements hence the results can be used to create devices that can be used in the investigations of the aforementioned open questions.

Another important problem that we have not touched upon is the delayed bilateral teleoperation synthesis problem that somewhat dominated the literature as if the undelayed case is completely studied. To justify our deliberate choice we distinguish two cases; there is a strong possibility backed by various studies that there exists an upper bound on the delay duration a human operator can cognitively compansate for during a bilateral teleoperation task. Beyond this delay value the human cannot associate the remote motion with the local device motion. Therefore let us denote this upper bound by T whatever it might be other than being very likely to be around 1 s, then we have the following obvious dichotomy,

- The actual transmission delay is higher than T,
- The actual transmission delay is lower than or equal to T.

In the first case, we believe that there is no need to even consider the problem since it is even harder to find the relevant performance objectives of how a human operator can be made to immerse into the task with an excessive time delay. In the second case, if there is significant time delay, one can use the multipliers given **??** for delay uncertainties and utilize it in the synthesis method given in **??** directly, with guaranteed improvements over the existing techniques. Additionally, if the communication delay is of the time-varying nature, one can always buffer the input/output to regularize the delay and use the known upper bound of the buffer period. The reason why this would always give a better performance is simply because the existing time-varying delay robustness analysis and synthesis tools are simply too conservative. Utilizing them surely would lead to stable interconnections but at the cost of unacceptable low performance levels which undermines the motivation the problem. Dealing with a known constant time-delay is, in turn, much easier and sharper results can be obtained. Note that practically every packet-switched network video/audio stream protocol use such buffering schemes unlike the vast majority of the time-delay teleoperation literature. In fact, this is not even a control-theoretical issue and should be left to digital communication experts for the optimal methods which go well-beyond control design knowledge. Moreover, the problem is far more sophisticated than the choice between TCP or UDP protocols.

Following this argument, we have the following conclusions elaborated in this thesis;

1. The bilateral teleoperation is fundamentally an interdisciplinary problem. Current literature underestimates the broadness of the scope of this technology and claims to solve a stability problem that is not inline with the actual bilateral teleroperation. The majority of the proposed problem formulations are of *What if we had sampling, two users, time-varying delay?* nature. Though, these scenarios are certainly worth considering, the proposed solutions only handle the stability issues. Our first conclusion emphasizes this;

   The bilateral teleoperation problem is not a typical control problem in which stabilization is the crucial point and achievable performance is an extra bonus. Without the required performance levels, a stable bilateral teleoperation system is useless.It might even decrease the human task performance.

2. As we have shown in **??**, the 2-port network modeling framework is not general enough to capture the problem in its entirety. Over the last two decades, certain derivations are established as facts for the perfect transparent device however one can still obtain better designs with alternative methods that do not obey the predicted performance conditions which are stated in numerous sources. If the following definition of transparency is adopted

   > Transparency is defined, meaning that the human operator should ideally feel as if directly acting in the remote environment (is not able to feel the technical systems/communication network at all).. ([49])

   which seems to be the case in the literature, then there is a discrepancy between what is being sought after and the corresponding formulation.

   Transparency objective that relates the performance to the operator feel and comfort with the definiton above does not necessarily imply that an ideal

teleoperation system should have a hybrid system representation $\begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix}$. This formulation completely ignores the human perception and moreover it is impossible to achieve. Additionally, as a control objective it relies on naive control concepts such as exact dynamics cancellation and plant inversion. In a time-varying system these arguments are invalid.

3. A vast majority of the network-theory based stability conditions can be rederived by the IQC framework in a lossless fashion. Due to this equivalence there is no added value of using scattering transformations or wave variables over the proposed framework.

   Insisting on the network theoretical treatment of the subject is a matter of preference. IQC framework already covers the classical methods and offers significantly larger set of possibilities to be utilized in stability analysis and controller synthesis. Here the emphasis is on the anachronistic focus of the literature.

4. As we have shown via a simple implementation, high-performance controllers can be designed using a sufficiently accurate model of the system and careful simplifications by the robust control design methodology.

   The D-K iteration with dynamic multipliers leads to significantly less conservative results compared to static multiplier based designs which includes wave-variable based-and passivity based methods. The disadvantege of model based design is the weight selection and that is a significant obstacle in judging the true optimality of the design. Even in the cases where the problem solution is guaranteed to be optimal, the design itself due to the performance weights selection can be non-optimal. However, this difficulty is not in par with the conservative methods. In other words, this difficulty can be overcome with educated trial-and-error phase. A conservative method does not permit such by-pass steps.

APPENDIX A

Network Theory Primer

In this appendix, we provide a collection of basic network theory concepts for the convenience of the nonexperts of the field, to be used as a quick reference while we discuss the tools used in the bilateral teleoperation studies. Our focus would be on interconnections and stability of these interconnections hence circuit theory preliminaries and physics of the components are omitted.

A.1 Terminology

We start with ideal circuits for which the external influences such as the magnetic interference, temperature gradient as well as internal characteristics such the conductor element length and resistance etc. are negligible. Hence a signal traveling through a conducting medium between location A and B distorted i.e., if an arbitrary property of the signal at any point between and including A and B is measured, we obtain the same results. This allows us to use the simplifications in block diagrams and calculations that point A and B have the same measurable characteristics through time. This is typically shown with a path connecting A and B. The interpretation is that A and B and also every other point on that path share the same variables of interest on that line. Therefore, A and B are said to be interconnected terminals connected by a "wire". Clearly creating terminals are as simple as cutting the connection arbitrarily on this path. Often, we define hypothetical terminals as if there were distinct points on the circuit and we have connected them artificially.

Following Jan C. Willems' formulation for a systematic definition of terminals and ports in [129]; an electrical circuit is a device, a black box, with wires so-called terminals through which the circuit can interact with its surroundings. In electrical circuits, the interaction takes place via the electrical voltage drop across the terminals and the electrical current that flows through the black box. Therefore each terminal admits two real variables attached to it, the potential and the current. Conventionally, the current is denoted with a positive number when it flows into the circuit. Thus, an interconnection is connecting a wire from terminal A of the black box (x) to B of (y) enforcing the following to hold

$$V_A = V_B \quad \text{and} \quad I_A = -I_B$$

Then, we can look at the resulting interconnected system (z) as (x) and (y) combined and exhibiting the same phenomenon at their terminals A and B.

The collection of physically attainable phenomena are abstracted with the notion of the behavior set ([101]): Consider a circuit with N terminals. Let $\mathcal{B} \subseteq (\mathbb{R}^N \times \mathbb{R}^N)^{\mathbb{R}}$

denote the behavior set that is defined as the set of all admissible potential and current trajectories compatible with the network architecture at each terminal. Here $(\mathbb{R}^N \times \mathbb{R}^N)^{\mathbb{R}}$ denotes the set of all maps $f : \mathbb{R} \to \mathbb{R}^N \times \mathbb{R}^N$ e.g. each terminal voltage and current evolution through time and $\mathcal{B}$ is the restriction to the maps that are compatible with the network structure. Roughly speaking, behavior set excludes all the trajectories that are physically impossible to attain by the black box. Thus, when it is said that a particular trajectory is in the behaviour set i.e.,

$$(V_1, \ldots, V_N, I_1, \ldots, I_N) := (V, I) \in \mathcal{B}$$

it implies that there exists an initial condition $(V(0), I(0))$ such that (V, I) is a an admissible trajectory through time (with a particular external excitation sequence if present).

Assuming a conservative magnetic field, a circuit can be modeled via the well-known Kirchhoff voltage and current laws compactly described as

$$(V, I) \in \mathcal{B} \implies (V + \alpha\mathbb{1}, I) \in \mathcal{B} \quad \forall\alpha \in \mathbb{R}^{\mathbb{R}} \tag{KVL}$$

$$(V, I) \in \mathcal{B} \implies \sum_{k=1}^{N} I_k = \mathbb{1}^T I = 0 \tag{KCL}$$

where $\mathbb{1}$ denotes a vector with all entries are equal to 1 whose size is clear from the context.

Let, $P \subseteq \{1, \ldots, N\}$ denote an m-tuple selection of indices out of N terminals of a circuit. Then, terminals P_i for all $i \in P$ are said to form a port if

$$(V, I) \in \mathcal{B} \implies p^T I = 0 \tag{Port KCL}$$

where p is a vector with kth entry being 1 if $k \in P$ and 0 otherwise. This is nothing but a reformulation of the well-known port condition from circuit theory. Thus, we can also define a port as the set of terminals that satisfy port KCL. Given a port with n-terminals with V, I denoting the through and across variables, the instantaneous power is given by

$$P = \sum_{k=1}^{n} V_k(t) I_k(t)$$

and the energy transfered in the time interval is given by the total power delivered to/from that port in the time interval $[t_1, t_2]$:

$$E = \int_{t_1}^{t_2} \sum_{k=1}^{n} V_k(t) I_k(t) dt$$

These formulas hold only if the terminals form a port and a port can have arbitrary number of terminals e.g., op-amps, transistors, $Y - \Delta$ resistance networks are examples for three terminal ports.

Using a mechanical-electrical analogy, the mechanical teleoperation devices are converted to a network of ports. In network theory applications to bilateral teleoperation, the "system" refers to the network model that is hypothetically disconnected (thus admitting virtual terminals) from its "surroundings" such as the "load" and the "source" of a circuit. This system is allowed to interact with its surroundings via "ports". In our context, load refers to the environment that is to be explored and the source is the human exploring the environment from a distance via the teleoperation system.

Remark A.1. *We have to note that, in this formulation, a single mass can not be modeled as a* 1*-port; mass does not satisfy the port KCL unless it is thought to be applying an opposite force to a fixed inertial frame at a distance. This is why the electrical analog of a mass (in the force-current context) is required to be a* grounded *capacitor. The interested reader is referred to [117] for the interesting story of the development of an exact mechanical analogue of a capacitor,* the inerter *which is succesfully implemented by McLaren Mercedes and Renault F1 teams and being used since 2005*[1]*. We also refer to [129] for a comprehensive analysis together with the common pitfalls and nonintuitive power/energy results. Though, the inappropriateness of view of input/output formalism which is adopted also in this thesis is brought to attention in numerous studies by Jan C. Willems and his colleagues, we are obliged to use the input/output formulation as we have no results regarding the behavioral approach to bilateral teleoperation systems (yet). However, the potential of a behavioral modeling of teleoperation systems is unavoidable if the engineer insists on "physics matching" as the performance objective covered in Chapter 3.*

Since every two-terminal port can be characterized by two variables ("through" and "across" quantities), it is possible to characterize the interconnected n-port networks as if one quantity is due to the other. This is done by imposing an artificial causality scheme; two of these time-dependent trajectories can be selected as free variables and the remaining ones become dependent variables ([101]). This is the simplest kind of input/output view of physical systems via treating one port variable as the *cause* and the other one as the *effect* of this cause e.g. the current is due to the voltage drop across the terminals or vice versa.

Depending on the choice of the free variables, the system can be expressed in terms of impedance, admittance and hybrid parameters for two-port networks and their combinations for general n-port network interconnections. In the cases where the two-port is LTI, with a slight abuse of notation, we will use the term "immitance" matrix to refer to any of these representations. Suppose that a two-port immitance matrix is partitioned as

$$\begin{pmatrix} q \\ y \end{pmatrix} = \begin{pmatrix} G_1 & G_2 \\ G_3 & G_4 \end{pmatrix} \begin{pmatrix} p \\ u \end{pmatrix}$$

where q, y, p, u represent the flow (current, velocity etc.) and the effort (potential difference, force etc.) signals. Then, obtaining one representation from another is

[1] According to the official statements.

possible by a combination of the following elementary "permutation" and "partial inversion" operations:

$$\begin{pmatrix} q \\ y \end{pmatrix} = \begin{pmatrix} G_2 & G_1 \\ G_4 & G_3 \end{pmatrix} \begin{pmatrix} u \\ p \end{pmatrix}, \tag{Permutation}$$

$$\begin{pmatrix} p \\ y \end{pmatrix} = \begin{pmatrix} G_1^{-1} & -G_1^{-1}G_2 \\ G_3G_1^{-1} & G_4 - G_3G_1^{-1}G_2 \end{pmatrix} \begin{pmatrix} q \\ u \end{pmatrix}. \tag{Partial Inversion}$$

In the latter operation it is assumed that the inverse exists. The existence of inverses are limiting the realizability of networks as impedance or admittance matrices. Moreover, in [2], it has been shown that a hybrid matrix realization is always possible regardless. This is yet another artifact of input/output formulation. However, since we are interested in the asymptotical stability of the complete interconnection including the nominal stability, such problematic cases are not within the scope of the practical interest.

For our purposes, we consider only the immitance matrices that describe G as an input-output mapping (as opposed to transmission or ABCD parameters) as follows:

$$\begin{pmatrix} q \\ y \end{pmatrix} = \begin{pmatrix} G_1 & G_2 \\ G_3 & G_4 \end{pmatrix} \begin{pmatrix} p \\ u \end{pmatrix}, \begin{pmatrix} p \\ u \end{pmatrix} = \begin{pmatrix} \Delta_s & 0 \\ 0 & \Delta_l \end{pmatrix} \begin{pmatrix} q \\ y \end{pmatrix}. \tag{A.1}$$

Therefore, the overall interconnection can be depicted by the block diagram given in Figure 2.2a. In relation to teleoperation, the blocks Δ_s and Δ_l refer to the human and the unknown environment.

A.2 Passivity Theorem

In this section passivity related important concepts are defined in a compact fashion. Nevertheless, the material given here is well-known and can be found in many classical sources such as [27, 47, 112]. We chose to follow [27] closely for the presentation style.

Let V be a linear space equipped with a scalar product, $\mathcal{T}$ be the index set of time and F be a class of functions $x : \mathcal{T} \to V$.

Definition A.2. *A linear truncation operator P_T is defined on F as*

$$P_T(x)(t) = \begin{cases} x(t) & \text{for } t \leq T \\ 0 & \text{for } t > T \end{cases} \tag{A.2}$$

In most of the cases, $\mathcal{T}$ is the closed positive real line and $V = \mathbb{R}^n$, hence the scalar product becomes the inner product defined on $\mathbb{R}^n$. The subscript $\cdot_T$ will be used as a shorthand notation for $P_T(\cdot)$. We also define $\mathcal{H}$ and its extension $\mathcal{H}_e$ as

$$\mathcal{H} := \left\{ x \in F \mid \|x\|^2 = \langle x_T, x_T \rangle < \infty \right\}$$

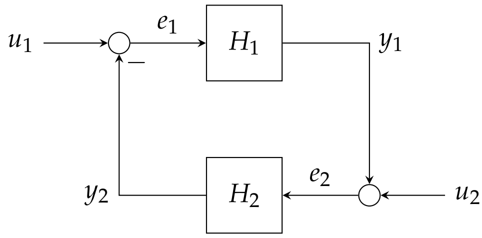


Figure A.1: Negative feedback interconnection

and

$$\mathcal{H}_e := \left\{ x \in F \mid \forall T \in \mathcal{T}, \|x_t\|^2 = \langle x_T, x_T \rangle < \infty \right\}$$

Definition A.3. *Let $H : \mathcal{H}_e \to \mathcal{H}_e$. H is said to be passive if and only if there exists a constant β such that*

$$\langle Hx, x \rangle_T \geq \beta \quad \forall x \in \mathcal{H}_e, \forall t \in \mathcal{T}$$

If moreover, there exists positive real number δ such that

$$\langle Hx, x \rangle_T \geq \delta \|x_T\|^2 + \beta \quad \forall x \in \mathcal{H}_e, \forall t \in \mathcal{T}$$

H is said to be strictly passive.

The scalar β is used to model the initial offset for nonlinear systems and will be taken as zero since we would be focusing on linear systems exclusively.

Definition A.4. *For an LTI operator H, passivity is equivalent to the corresponding transfer function $H(s)$ being positive real:*

$$\begin{aligned} \operatorname{Re}\{H(i\omega)\} \geq 0 &\iff \hat{u}^*(i\omega) \operatorname{Re}\{H(i\omega)\} \hat{u}(i\omega) \geq 0 \\ &\iff \int_{-\infty}^{\infty} \hat{u}^*(i\omega) \operatorname{Re}\{H(i\omega)\} \hat{u}(i\omega) d\omega \geq 0 \\ &\iff \int_{-\infty}^{\infty} [H(i\omega)\hat{u}(i\omega)]^* \hat{u}(i\omega) d\omega \geq 0 \end{aligned}$$

for all $\omega \in \mathbb{R}_e$ and for all $u \in \mathcal{L}_2^n$. Furthermore, if the condition

$$\int_0^{\infty} H(u)(\tau)^T u(\tau) d\tau \geq \delta \|u\|_2^2 + \epsilon \|H(u)\|_2^2$$

is satisfied with $\delta > 0$, $\epsilon = 0$ (or $\delta = 0$, $\epsilon > 0$) then the operator is said to be Strictly Input (Output) Passive with level δ (or level ϵ) respectively.

Suppose we are given with two dynamical systems $H_1, H_2 : \mathcal{H}_e \to \mathcal{H}_e$ for which the system structure is given in time-domain with

$$\dot{x} = f(x, e) \tag{A.3}$$
$$y = h(x, e) \tag{A.4}$$

for both systems where $f : \mathbb{R}^n \times \mathbb{R}^m \mapsto \mathbb{R}^n$ is locally Lipschitz and $h : \mathbb{R}^n \times \mathbb{R}^m \mapsto \mathbb{R}^p$ is a continous function satisfying $f(0,0) = 0$, $h(0,0) = 0$.

Definition A.5 (Well-posedness)**.** *Consider the system interconnection given in Figure A.1. The interconnection is said to be well-posed if there exist unique solutions e_1, e_2 to the equations*

$$e_1 = u_1 - h_2(x_2, e_2) \tag{A.5}$$
$$e_2 = u_2 + h_1(x_1, e_1) \tag{A.6}$$

for all admissible (x_1, x_2, u_1, u_2). In the LTI case, assume that the respective transfer functions $H_1, H_2 \in \mathcal{RH}_\infty$. Then the interconnection is well posed if $(I - H_1 H_2)^{-1}$ is a proper transfer matrix.

Note that, in our context u_1, u_2 model the voluntary part of the human/environment force input as mentioned in Chapter 2.

Theorem A.6. *Consider the well-posed feedback interconnection shown in Figure A.1 and described by Equations (A.5) and (A.6). Assume that there exist constants γ_1,β_1, δ_1,β_1',ϵ_2,β_2' such that the following conditions hold*

$$\|H_1 x\|_T \leq \gamma_1 \|x_T\| + \beta_1 \tag{A.7}$$
$$\langle x, H_1 x\rangle_T \geq \delta_1 \|x_T\|^2 + \beta_1' \tag{A.8}$$
$$\langle H_2 x, x\rangle_T \geq \epsilon_2 \|H_2 x_T\|^2 + \beta_2' \tag{A.9}$$

for all $x \in \mathcal{H}_e$ and for all $T \in \mathcal{T}$. If

$$\delta_1 + \epsilon_2 > 0 \tag{A.10}$$

then, $u_1, u_2 \in \mathcal{H}$ imply that $e_1, e_2, y_1, y_2 \in \mathcal{H}$

A well-known absolute stability analysis result for the LTI network is due to Llewellyn [81]. An explicit indication of the frequency dependence is omitted for notational convenience.

Theorem A.7 (Llewellyn's Criteria)**.** *A two-port network N, described by its transfer matrix*

$$N(i\omega) = \begin{pmatrix} N_{11}(i\omega) & N_{12}(i\omega) \\ N_{21}(i\omega) & N_{22}(i\omega) \end{pmatrix}$$

and interconnected to passive LTI termination immitances as in Figure 2.2a, is stable if and only if

$$R_{11} > 0 \text{ or } R_{22} > 0, \tag{A.11}$$

and

$$4\left(R_{11}R_{22} + X_{12}X_{21}\right)\left(R_{11}R_{22} - R_{12}R_{21}\right) - \left(R_{12}X_{21} - R_{21}X_{12}\right)^2 > 0 \tag{A.12}$$

or

$$2R_{11}R_{22} - |N_{12}N_{21}| - \mathrm{Re}\{N_{12}N_{21}\} > 0 \tag{A.12$'$}$$

for all $\omega \in \mathbb{R}_e$, where R_{ij} and X_{ij} denote the real and imaginary parts of N_{ij} respectively.

As is the case for Llewellyn's stability conditions, it is straightforward to derive unconditional stability tests if the network is represented by scattering parameters. In what follows, we denote transformed passive LTI uncertainties with $\tilde{\Delta}_s, \tilde{\Delta}_l$ which are unity gain bounded. The corresponding interconnection is supposed to be given by the loop equations $q = Sp$, $p = \tilde{\Delta}q$ i.e.

$$\underbrace{\begin{pmatrix} q_1 \\ q_2 \end{pmatrix}}_{q} = \underbrace{\begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix}}_{S} \underbrace{\begin{pmatrix} p_1 \\ p_2 \end{pmatrix}}_{p}, \quad \begin{pmatrix} p_1 \\ p_2 \end{pmatrix} = \underbrace{\begin{pmatrix} \tilde{\Delta}_s & 0 \\ 0 & \tilde{\Delta}_l \end{pmatrix}}_{\tilde{\Delta}} \begin{pmatrix} q_1 \\ q_2 \end{pmatrix}. \tag{A.13}$$

Rollett's conditions ([74, 107, 120]) for stability are then formulated as follows:

Theorem A.8. *Consider the same network given in Llewellyn's criteria which is represented in scattering parameters. The interconnection is stable if and only if the inequality*

$$K = \frac{1 + |\nabla|^2 - |S_{11}|^2 - |S_{22}|^2}{2\,|S_{12}S_{21}|} > 1 \tag{A.14}$$

holds for all frequencies together with an auxiliary condition in terms of $\nabla = S_{11}S_{22} - S_{12}S_{21}$. This extra condition can be stated in at least five different ways, such as

$$1 - |S_{11}|^2 > |S_{12}S_{21}| \;\; \text{or} \;\; (1 - |S_{22}|^2) > |S_{12}S_{21}|\,.$$

(See [32] for further details).

In [32], Edwards and Sinsky reduced Rollet's conditions to a single quantity denoted as μ to be checked for being greater than unity for all $\omega \in \mathbb{R}_e$.

Theorem A.9. *Verifying Rollet's conditions is equivalent to verifying the single condition*

$$\mu := \frac{1 - |S_{11}|^2}{|S_{22} - S_{11}^*\nabla| + |S_{12}S_{21}|} > 1 \qquad \forall \omega \in \mathbb{R}_e.$$

APPENDIX B

A Terminological Classification

In this chapter, we give the general outline how we have classified the touch technologies to isolate bilateral teleoperation which is our main focus. Moreover, we give some specific details about the human body for a quick reference.

B.1 The Adopted Terminology

The somatosensory system involves complicated chemical and mechanical components and there are different layers of sensory mechanisms that contribute to the overall perception. Hence, it is not always directly possible to use a reduction argument that simplifies the involved processes. In fact, depending on the type of sensation, different layers of these mechanisms are excited.

The main two branches of technology relating to the touch perception are the tactile and kinesthetic feedback (as we define below). The terminology is yet to reach a steady-state standard, however, what follows below seems plausible considering the variations and nuances found in the literature. Since there is no fixed definition for such perception we would use a rough classification based on the magnitude-frequency content of the motion[1]. We have to emphasize that this classification is completely conceptual and only serves to exclude the parts that are not studied in this thesis. Therefore, we refer the reader to the authoritative resources of the involved physiology, e.g., [61]. We start with a somewhat detailed sensory classification to support our choice of amplitude-frequency based grouping.

Typically, the touch perception is also classified into these two groups; tactile feedback and kinesthetic (proprioceptive) feedback, hence the naming of the involved technologies. For practical purposes, one can use the analogy of parallel connected high-pass and low-pass filters to indicate the frequency band of interest respectively. For our control-oriented context, let us define a few key concepts with an engineering point of view.

In physiology, the sensors on the skin which take different physical measurements are called *receptors* and prefixed with their area of specialization such as *thermoreceptors*, *mechanoreceptors*, *nocioreceptors* (pain) etc. The signals that trigger an action on these receptors are denoted as the *stimuli*. In case of a stimulus, these receptors, through some chemical processes, exhibit a series of *action potentials* or electrical discharge pulses i.e. a *spike train*. In the engineering terminology, this can be modeled as a nonuniform Dirac comb with varying frequency as a function of the stimuli intensity or a digital frequency modulation (FM) signal. The frequency

[1] In the Fourier analysis sense

increases with the stimulus intensity. Furthermore, at the input side of this sensor there is a dead-zone nonlinearity hence the stimuli should exceed a particular threshold to trigger a receptor firing.

There is also another process, called *neural* or *sensorial adaptation* which quantifies the frequency decay of firing under constant stimulus. We can see the tangible effect of this process frequently e.g., our nose looses the sensitivity to a powerful smell if exposed to it for some time or we stop noticing the touch of glasses on the face or the ring on the finger. Some sensors have a slow decay rate whereas others decay in a matter of seconds. The slow sensors often called the *slowly adapting (SA)* and others are called *fast adapting (FA)* or *rapidly adapting* type [13].

As shown in Table B.1, and also surveyed in [70], there are four main types of mechanisms that are utilized for the force and texture sensing with varying operating conditions and spatial authority. Although all contribute to the high frequency stimulus perception with varying levels, slowly adapting receptors are mainly tuned to detect the low frequency information range (up to 30 Hz). The fast adapting Meissner(FAI) and Pacinian(FAII) Corpuscles can be excited in the frequency range of $[10{,}60]$ Hz and $[60, 1000]$ Hz respectively. Thus, small-area receptors (Type I) are excited with the rate of skin deformation whereas relatively large-area receptors (Type II) are with the acceleration of the skin. Moreover, FAI units are located closer to the skin surface, have high unit density with small surface area forming a grid of sensors. On the other hand, FAII units are located in the subcutaneous tissue and work as a single load cell with relatively large surface area. This allows experts to assume that FAI units are mainly responsible for spatial information about the skin deformation and FAII units are responsible for the high frequency information with response delays in the range of $[50{,}500]$ ms [133]. Another interesting note in [70] is that due to their single unit nature FAII units offers the possibility to provide high frequency information with a single vibration display, while for FAI units it is more appropriate to supply an array of haptic displays for lower frequency range.

The SAI disk receptor has a small, localized receptive surface area as opposed to the SAII with a large field with a decaying sensitivity from center to the edges. Individual Ruffini endings are excited by stretch of the skin in specific directions. The majority of hand receptors consists of FAI units ($> 40\%$), then SAI units cover almost a quarter which followed by SAII covering 19% and FAII 13%.

B.1.1 *Weber ratio and Just-Noticeable-Difference(JND)*

The Weber ratio is defined as the ratio between the minimal stimulus intensity change in any physical quantity that triggers a change perception and the intensity of the stimulus. In case of a constant or static stimulus, the ratio is denoted with Just-Noticable- Difference (JND). For engineering purposes, this derived unit can be beneficial to design the frequency behavior of the haptic systems which exhibit a particular sensitivity pattern.

Feature	Meissner Corpuscles (FAI)	Pacinian Corpuscles (FAII)	Merkel's Disks (SAI)	Ruffini Endings (SAII)
Rate of adaptation	Rapid	Rapid	Slow	Slow
Location	Superficial dermis	Dermis and subcutaneous	Basal epidermis	Dermis and subcutaneous
Mean receptive area	13 mm^2	101 mm^2	11 mm^2	59 mm^2
Spatial resolution	Poor	Very poor	Good	Fair
Sensory units	43%	13%	25%	19%
Response frequency range	[10,200] Hz	[70,1000] Hz	[0.4,100] Hz	[0.4,100] Hz
Min. threshold frequency	40 Hz	[200,250] Hz	50 Hz	50 Hz
Sensitive to temperature	No	Yes	Yes	At $>$ 100 Hz
Spatial summation	Yes	No	No	Unknown
Temporal summation	Yes	No	No	Yes
Physical parameter sensed	Skin curvature, velocity, local shape,flutter, slip	Vibration, slip, acceleration	Skin curvature, local shape, pressure	Skin stretch, local force

Table B.1: Functional Features of Cutanous Mechanoreceptors (Adapted from [133])

B.1.2 *Tactile Feedback*

Tactile feedback, in general, is utilized to distinguish fine details such as shape, curvature, vibration, acceleration, and texture perception. Hence, the high-frequency content of the touch information is indispensable to transmit such information. Since the amplitude of the motion at these frequencies are quite small, the palm and finger tissues act as a low-pass filter and avoid such information to penetrate into the skin. Thus, only a limited part of the sensors have access to this information.

A striking example to the mind-boggling quality of feedback is the Braille system used by visually impaired or disabled individuals (Figure B.1). The average reading speed with Braille system is about 125-150 words per minute ([1]) in contrast with 200-250 words per minute by eyesight.

Most of today's technological devices utilize this modality to send and receive information. Many mobile phone applications and a few gaming consoles such as Nintendo Wii™, Sony Playstation ™ etc., utilize short vibrational patterns to alert the user that some action has been performed e.g. the user hovers over a hot spot on the screen or some moving object hits an obstacle etc.

The tactile technology is, thus, concerned with the vibrational pattern and high-frequency sweep of stimuli. Communication via small vibrational or textural subtleties allows the tactile technology to focus on the low-stroke, high-bandwidth haptic displays. The required low-stroke action is often generated by a small and agile electrical motor with a load eccentricity with respect to the rotor shaft axis. The angular velocity of the motor then defines the frequency of the vibration. Since the involved mechanisms on the human limbs and hands are rapidly adapting, the bus speed in this modality can be very high compared to the kinesthetic feedback in which the human should track and pick out patterns from relatively slow and large-amplitude motion profiles via measuring muscle stretch amount and various other quantities.

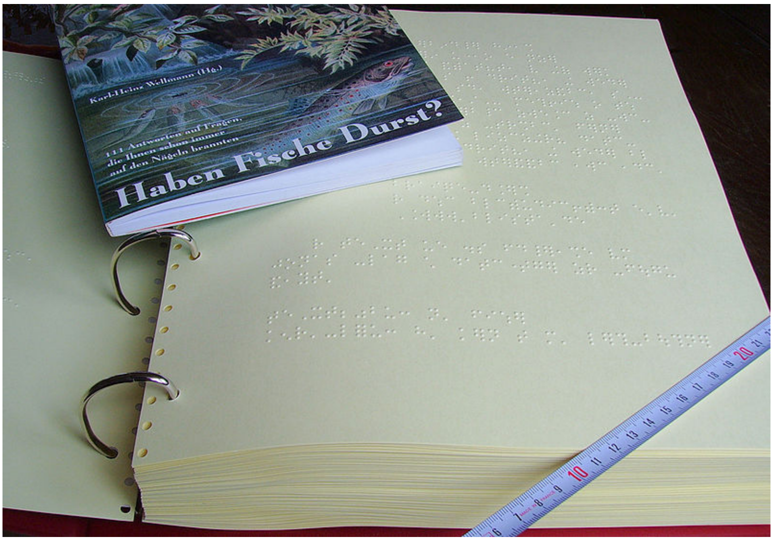


Figure B.1: A comparative case for the spatial resolution: The volume of the same content in the form of Braille and regular text (Karl-Heinz Wellmann, [Wikipedia:Brailleschrift])

B.1.3 *Kinesthetic (Proprioceptive) Feedback*

Proprioception[2] (*Proprius+perceptio* : the act of gathering/perceiving of own) is the ability to sense the limb configurations and motion without using a visual aid (cf. vestibular feedback which is to used to sense the balance and the spatial body orientation). Kinesthetic feedback, together with limited force sensing abilities of muscles and tendons and relatively small interference of tactile feedback system, is "vital" to have control of our own body. It's a futile attempt to describe the importance of this often overlooked perception (or hidden sense) other than referring to the 1998 BBC *Horizon* documentary "*The man who lost his body*" and the paper [82] about Ian Waterman. He is the only person known to date who can cope with the loss of proprioceptive feedback while still being able to stand up, walk, maintain posture etc. without any artificial support. Unfortunately, he is completely dependent on his visual feedback as he tirelessly computes trajectories of his body parts on-the-fly to compensate for the loss of kinesthetic feedback even when gesturing with hands.

Thus, whether we are aware of it or not, proprioception is indispensable for us to survey the environment. The force on our limbs, our body configuration at that instance, and our body motion are sensed via sensors in the joints, muscle tendons and muscles themselves. Unlike the tactile feedback characteristics given previously, the compliance, the distribution of pressure and and the shape information is measured in a relatively coarse fashion. Hence, when combined with tactile feedback

[2] We will not go into the nuances between kinesthetic and proprioceptive feedback

and the brain's internal comparison database, we use an unparalleled sophistication to actually perceive the environment without using any visual feedback, even if the object is foreign to us. In [8], a convenient summary of the properties is presented. Distilling even further for a general picture about the proprioception, we provide the following quick facts.

The compression or stretch of the receptors covered previously changes the amplitude of the impulse of the action potential which, in turn, used as the position information. Similarly the frequency of these firings are interpreted as the velocity information. For the limb position and motion, the bandwidth of the kinesthetic sensing is around [20,30] Hz with varying accuracy in terms of JND around $[0.8, 2.5]^{\circ}$. Moreover, the control bandwidth is reported to be task-dependent: [1,2] Hz for unexpected signals; [2,5] Hz for periodic signals, < 5 Hz for generated or learned trajectories and finally about 10 Hz for reflex actions.

Regarding the force sensing, it has been experimentally demostrated that pressure JND decreases as the pressure area increases; e.g., the overall average JND drops to 3.7% with a contact area of $20.27\,\mathrm{cm}^2$ from 15.6% with a contact area of $1.27\,\mathrm{cm}^2$.

The kinesthetic technology can be used in conjunction with tactile technology to provide a full manipulative immersion. Moreover, in the case of *exoskeletons*, it can be the essential ingredient to protocol between the environment and the human body. Especially, rehabilitation patients can benefit from such technologies via combining the visual and the kinesthetic feedback to amplify the disabled or impaired control action of the problematic limb. Thus, kinesthetic technology is mainly involved as low-frequency based manipulative or explorative motion tasks. Considering the current hardware limitations, many tasks depend primarily and rather primitively on kinesthetic cues for bilateral teleoperation and virtual reality applications.

B.1.4 *Teleoperation*

Teleoperation is the general name for providing human actions to a different media that is not accessible (or only in a costly way) to direct contact in a precise fashion. Microcomponent assembly, minimal invasive surgery (MIS), space station maintenance and construction, underwater exploration and construction are all typical application examples that the human either can not be present or physically interact with comfortably. The *da Vinci*™ surgery robot from Intuitive Surgical Inc. is a well-known example of *unilateral* human manipulation to achieve high precision tracking with surgical tools inside very tight incisions.

However, as often motivated by the *bilateral* teleoperation studies, the human operators, expecially the experienced ones, often lack the ability to employ their precise tactile and kinesthetic abilities to take decisions or to monitor their progress since they rely on vision feedback from the cameras exclusively. In some particular practices, surgeons might resort to inserting their fingers inside the incision to feel the relevant tissue stiffness difference to get a better spatial understanding when the view is contaminated with blood or other bodily fluids. In the case of an obstruction during an insertion of an instrument into the body, they might tend to correct the instrument based on their force feel at hand. Hence, the realism is diminished as opposed to the increased precision by the teleoperation methods.

B.1.5 *(Computer) Haptics*

In general, haptics technology encompasses all the items that have been covered up to this point. However, it is also often used as a placeholder for the concept of creating artificial or virtual object perception with a force-feedback capable device. Computer haptics also have additional challenges such as rendering deformations in case of a soft object or realistic graphical presentation of object interaction in terms of collisions etc. In other words, not only the forces are important but the consequences of these force interactions need to be handled in a precise fashion. Conversely, computer haptics is free from the hardware limitations or the noisy measurements, as the objects and the physical laws that they should obey are computer generated.

B.1.6 *Virtual Reality*

This term refers to a set of artificially generated immersion techniques that can rely on either a single or multiple modalities at once. The common applications consist of special googles that cover the human vision. By tracking the head movements and adjusting the scene that is projected onto the special headset, the user can immerse into the artificial environment. Combined with headphones and if possible with haptics, the experience can be substantially improved. Especially haptics can increase the immersion level much more compared to only visual+audio supplements since otherwise the realism can be destroyed quickly if the user tries to touch any object or surface while actually waving his hand. The persuasiveness of the scene depicted on the headset needs to be backed up with at least a slight kinesthetic feedback, if not tactile, since the loss of tactile feedback is relatively less important in an exploration task.

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