Towards a Model of the Human Hand: Linear System Identification of the Human Grasp

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Abstract: In a haptic system the human operator acts on an active mechanical device, which lets the user sense and manipulate computer-generated or real remote environments. From the considerations arising in the control of such systems, accurate dynamic modeling of the human hand grasping haptic devices could improve stability analysis and device control design. This paper develops an experimental characterization of the behavior of a human hand holding a haptic knob in a three-fingered grasp. Traditional system identification techniques are used, moreover, three different linear and time-invariant lumped dynamic models of the human hand, are presented and discussed.

Key-Words: biomechanics, identification of mechanical systems, haptic systems

1 Introduction

In a haptic master-slave system, the human operator generally grasps a master device which transmits the operator's commands to a remote slave. The slave follows the master input and interacts with a real or virtual environment, usually feeding back signals which are employed by the master to generate a force feedback for the operator, by means of electrical servo-actuators. As a consequence the user can feel as if he were manipulating the remote environment directly (Burdea, 1996). Clearly, haptic displays are becoming increasingly popular in virtual reality and simulated environment applications.

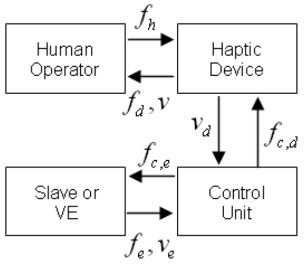

Figure 1: Typical control scheme of a haptic MS system

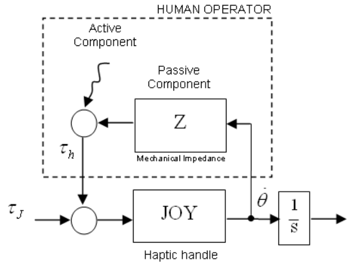

Figure 2: Human operator components

In order to design inherently stable haptic devices or to implement stability-enhancing control schemes, one needs to know and to take into consideration at least the chief mechanical properties of a hand and their influence in the global system dynamics. In fact as shown in Fig.1 and in Fig.2 the operator's dynamics plays a role of paramount importance in the control loop (and so in the global dynamics) of a haptic system.

For simplicity, it is possible to represent a human operator's effect on a haptic device as the sum of an active component (due to the voluntary action of the operator on the device) and a passive component (Fig.2). In this work we are only dealing with the latter: the mechanical impedance ($Z(s)$), and in particular, the generalized mechanical impedance (admittance: $Y(s)$) which is the dynamic (history-dependent) relationship between force and velocity and is defined as the ratio, in the frequency domain, between the velocity of the operator's hand ($v(s)$), and the force applied on the operator ($F(s)$): $Y(s) = {}^{1}\!/_{Z(s)} = {}^{v(s)}\!/_{F(s)}$. Clearly, the availability of accurate models of the human hand would provide a highly valuable simulation tool for testing the performances of new haptic displays with increased repeatability, accuracy, and even with self tuning capabilities (Harwing and Wall, 1999).

Haptic displays may employ a wide variety of mechanisms for user interaction, including joysticks, thimbles, knob, and styli. The research activity described in this paper aims at characterizing the behavior of the human hand holding a haptic knob in a three-fingered grasp. The human hand is a complex system (e.g. it presents at least 21 degrees of freedom), however, many sources have supported the validity of reproducing of the human joint dynamics by means of linear models: in particular second-order models are commonly used. Most modeling approaches assume that the system is time-invariant, an assumption which only holds when activation levels in the muscles surrounding the joint remain constant. For a human hand in a handle grasp, this implies that:

- the grip is always constant,
- the motion about the origin is small to avoid changenges in kinematics,
- the muscle activation does not change to affect the stiffness or damping characteristics of the grasp.

This paper develops a characterization of the behavior of the human hand holding a haptic handle in a three-fingered grasp by using traditional system identification techniques. As a matter of fact standard system identification techniques provide a framework for the characterization of linear time-invariant systems. The aim of this work is to analyze the human hand dynamics when performing tasks on a one d.o.f. haptic knob, named "JOY". JOY is currently used as part of a Master-Slave system for neuro-surgery built at the DIMEG of the University of Padua. Admittedly, a better knowledge of the dynamics of the human grasp will help in the design and simulation of complex haptic systems, and will promote the development of improved control schemes for global haptic systems.

2 Previous work on human dynamics identification

Human joint dynamics has been carefully investigated over the years. As mentioned before a widespread approximation consists in adopting linear models holding only about an operating point. Moreover, time-invariancy for the system is commonly assumed to reduce the model complexity. Human joint dynamics has generally been studied considering commanded torque/force as the inputs, and their resultant position/angle vectors as the outputs. This approach is assumed to provide better results, especially at lower frequencies (Kearney and Hunter, 1990), when compared to the approach considering commanded position/angle trajectories as input. The model usually proposed for human joint dynamics is a simple second-order time-invariant one. Such a model as been adopted in the following references to describe the dynamic behavior of several human joints. Crowninshield (Crowninshield and al., 1976) found a model for the impedance of the human knee; Agarwal and Gottlieb (1977) and Kearney (Kearney and Hunter, 1982; Hunter and Kearney, 1982; Kearney and al., 1997) studied the human ankle dynamics; Harwin and Wall (1999) investigated the dynamics of the wrist. Becker and Mote (1990), after having studied the dynamics of the index finger in abduction/adduction, found that a second order mass-spring-damper model described the dynamics well for small displacements. Milner and Franklin (1995, 1998) worked on finger dynamics, for haptic application purposes, always proposing a second-order model. Hajian (1997) conducted an extensive study on the impedance of the human finger too.

To gain a better insight into the human finger and hand dynamics, it is necessary to consider the fundamental role fingerpads play in the vast majority of the mechanical interactions with the world. Indeed, fingerpads act as coupling elements between the hand and the grasped object. Pawluk and Howe (1999) investigated the dynamics of the fingerpad in compression. Wu (Wu et al., 2002) developed a two-dimensional, nonlinear finite model of the fingertip, to describe its properties under dynamic loading. In his PhD dissertation, Hasser (2002) proposed a linear time-invariant model to approximate the dynamics of the human hand in a one d.o.f. system, since a linear time-invariant model leads to a simpler stability analysis. Following a method similar to that of Hajian (1994), he proposed a second order rotational model of the fingertip for the human hand grasping a haptic knob. Hasser collected data concerning the torques applied and the angular displacement, then calculating both velocities and accelerations from displacement signals. He also presented a more complicated linear, time-invariant model of the fourth order for the hand, operating the same least-squares fitting method for a simplified state-space model. An interesting research has also been conducted by Fagergren (Fagergren et al., 2000), focusing on the dynamics of the human precision grip. A system identification study has been undertaken to find the transfer function describing the peripheral motor subsystem, from the motoneuron pulse to the final generation of a grip force between the tip of the index finger and the thumb. Classical subsystem identification was performed to characterize a specific subsystem in a complex biomechanical system. Once again a second order model was given as a result.

The choice of the input signal for the identification of human joint dynamics has always been limited by the fact that after even a very short period changes in muscle activation can be a threat to the supposed time-invariance. Muscle stretch reflex responses can be seen in EMG signals from the hand muscles in as little as $20-30ms$ (Milner and Franklin, 1995). Cutaneous slip reflexes can occur in fingers grasping an object at about $70ms$ after onset of slip (Johansson and Westling, 1984). Voluntary muscle activation occurs at longer latencies. For this reason, most authors (e.g. Hajian, 1997 and Hasser, 2002) applied and removed input stimuli rapidly, before any voluntary or reflexive muscle activation could occur. In particular, transient input stimuli, comprising a sequence of finite pulses lasting no longer than $20ms$ were applied as input signals. Such a study of the human hand dynamics on a very brief time scale is interesting to gain a model of the human hand during a contact with a virtual wall, but is of minor relevance to definition of a model suitable when the operator has to be kept in contact with a virtual environment for long periods, or when the haptic interface acts as an active guide for the operator as in the case of telerobotics or telesurgery.

3 Three dynamics models for the human hand

In this paper three linear, time-invariant and lumped models are adopted to try identifying the dynamic response of a human hand grasping a haptic knob: the three models are of an increasing level of complexity and are described in detail in the subsections below.

3.1 Second order model

A linear second order lumped model at the fingertip has been first proposed by Hasser, 2002. A mass spring damper approximation of the system is employed and described through the following model in state-space form:

$$\begin{bmatrix} \ddot{\theta}(t) \\ \dot{\theta}(t) \end{bmatrix} = \begin{bmatrix} -\frac{B}{J} & -\frac{K}{J} \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \dot{\theta}(t) \\ \theta(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{J} \\ 0 \end{bmatrix} T(t) \qquad (1)$$

where J is the hand inertia, and K and B are respectively the stiffness and damping constants (see Fig.3). On an identification task this model can be effectively employed by considering the torque $T(t)$ as the input, and the angular displacement $\theta(t)$ as the output. Such physical quantities can be experimentally measured by means of a torque transducer and an optical encoder.

3.2 Fourth order model

In order to get a better description of a hand dynamics a fourth order rotational model may be adopted. In this case, finger dynamics, fingerpad dynamics and actuator dynamics are treated separately .

The state-space form is:

$$\dot{\Theta}(t) = A\Theta(t) + BT(t) \qquad (2)$$

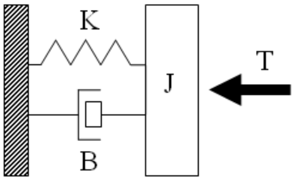

Figure 3: Linear second order model

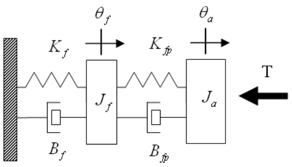

Figure 4: Linear fourth order model

where:

$$\Theta(t) = \begin{bmatrix} \dot{\theta}_a(t) & \theta_a(t) & \dot{\theta}_f(t) & \theta_f(t) \end{bmatrix}^T$$

$$A = \begin{bmatrix} -\frac{B_{fp}}{J_a} & -\frac{K_{fp}}{J_a} & \frac{B_{fp}}{J_a} & \frac{K_{fp}}{J_a} \\ 1 & 0 & 0 & 0 \\ \frac{B_{fp}}{J_f} & \frac{K_{fp}}{J_f} & -\frac{(B_f+B_{fp})}{J_f} & -\frac{(K_f+K_{fp})}{J_f} \\ 0 & 0 & 1 & 0 \end{bmatrix} \qquad (3)$$

$$B = \begin{bmatrix} \frac{1}{J_a} & 0 & 0 & 0 \end{bmatrix}^T$$

As shown in Fig.4, J_f, B_f and K_f describe the dynamics of the finger, while B_{fp} and K_{fp} represent the damping and stiffness coefficients of the fingerpad. J_a is the moment of inertia of the actuator and has to be estimated separately.
As far as system identification is concern T is the input signal (the active torque measured) and the only angular displacement which can be physically measured is θ_a.

3.3 Sixth order model

Time invariant second and fourth order models have been proved to have limitations mainly in terms of estimation of the moment of inertia (Kuchenbecker et al., 2003), so in this paper a higher order model is also considered. Precisely, here the dynamics of the two fingers actually involved in the grip is represented separately. J_{f1}, K_{f1}, B_{f1} are the parameters of the mass, spring and damper symbolizing the first finger, J_{f2}, K_{f2}, B_{f2} the parameters of the other finger. B_{fp1} and K_{fp1}, B_{fp2} and K_{fp2} represent the damping and stiffness coefficients for both the fingerpads. Furthermore, J_a is the moment of inertia of the actuator. The resulting system is depicted in Figure 5, and its dynamics is described by Eq.(4).

$$\begin{cases} J_a\ddot{\theta}_a + B_{fp1}(\dot{\theta}_a - \dot{\theta}_{f1}) + K_{fp1}(\theta_a - \theta_{f1}) + \\ +B_{fp2}(\dot{\theta}_a - \dot{\theta}_{f2}) + K_{fp2}(\theta_a - \theta_{f2}) = T(t) \\ J_{f1}\ddot{\theta}_{f1} + B_{f1}\dot{\theta}_{f1} + K_{f1}\theta_{f1} + \\ -B_{fp1}(\dot{\theta}_a - \dot{\theta}_{f1}) - K_{fp1}(\theta_a - \theta_{f1}) = 0 \\ J_{f2}\ddot{\theta}_{f2} + B_{f2}\dot{\theta}_{f2} + K_{f2}\theta_{f2} + \\ -B_{fp2}(\dot{\theta}_a - \dot{\theta}_{f2}) - K_{fp2}(\theta_a - \theta_{f2}) = 0 \end{cases} \qquad (4)$$

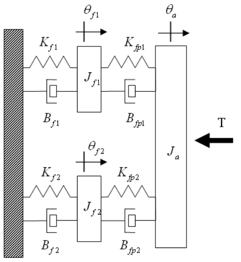

Figure 5: Proposed linear sixth order model for the human hand

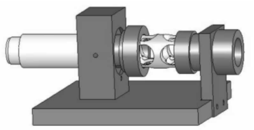

Figure 6: JOY haptic knob

Figure 7: Three-fingered grasp

It is not too simplistic an approach, however, to consider the dynamics of the two fingerpads to be the same, i.e. $B_{fp} = B_{fp1} = B_{fp2}$ and $K_{fp} = K_{fp1} = K_{fp2}$, thus obtaining a simpler model for the hand.

4 Testbed description

Experiments were performed using a one d.o.f. manipulandum, named "JOY" (Fig.6 and Fig.7). The system actuator is the 35NT2R-82-426SP Escap torque controlled DC brush motor. An Advanced Motion Controls C25A1B servo amplifier drives the motor with a PWM signal. A Sensoray 626 multifunction I/O board generates the command input to the servo amplifier. A Futek T5160 reaction torque sensor has been mounted on the shaft of the motor and connected to a Futek JM-2A amplifier module, to supply an independent torque measurements. A $40,000 cpr$ incremental encoder (Elcis X0045) has been mounted on the motor shaft, to measure angular displacements. Finally, a $40mm$ diameter knob completes the system.

As a first step towards the identification of the human hand dynamics, some preliminary study on the apparatus dynamics (the parameters J_a, B_a and K_a) has been carried out. In particular, an identification experiment showed that the coefficients B_a and K_a are always negligible compared to those of the human hand. The same experiment has allowed identifying the value of J_a (the apparatus inertia, comprehensive of motor rotor, shaft, torque sensor and encoder inertias). J_a is higher than human hand inertia and for this reason has to be considered during the analysis of the human hand dynamics.

5 System Identification

Six 23-27-year-old students took part in the experiments. The students (all with a good level of experience with haptic devices) were asked to keep their grip as constant as possible during the tests. Six tests were repeated for each student.

The tests carried out consist in providing a chirp torque reference to the actuator and in measuring both the torque actually exerted by the motor and the knob angular displacement. As an example, Fig.8 shows the time-histories of the input and output on a sample test.

The input chirp signal chosen is characterized by a frequency decreasing from $50Hz$ to $1Hz$, which is in accordance with the studies by Rosenberg, 1995, who recommended a force feedback bandwidth of at least $50Hz$, for haptic interfaces. The signal duration is $1s$, since the aim of this study is to attain a model for the human hand working on JOY within a telerobotic haptic system, on a time-scale longer than Hasser's $20ms$.

A sampling frequency of $1KHz$ is chosen for the torque sensor and the encoder signals. Both the displacements and the torque signals are filtered through a FIR lowpass filter. Then in order to obtain angular velocities, the displacement signals are filtered through a FIR differentiator (Oppenheim and Schafer, 1999). The approach followed to identify the system dynamic parameters is different form the one adopted by Hajian, 1997 and Hasser, 2002. Starting from equations describing the system dynamics in matrix form, they obtained the model parameters using the matrix division function in MATLAB. In this work instead, in order to calculate the parameters of the system we are investigating the matrix has be identified performing a prediction error estimate (`pem`) for an `idgrey` model structure describing the system, using the MATLAB System Identification Toolbox. The results obtained are briefly summarized in the figures from 9 through 15. In particular Fig.9 and Fig.10 show the periodigrams and the data spectra of the input and output signals obtained aggregating the experimental results. Figure 11, on the other hand, presents the experimental frequency response for the system. Figure 12 shows that the models of the second order do not differ substantially for all the six people involved in the experiment. Figures 13 and 14 capare

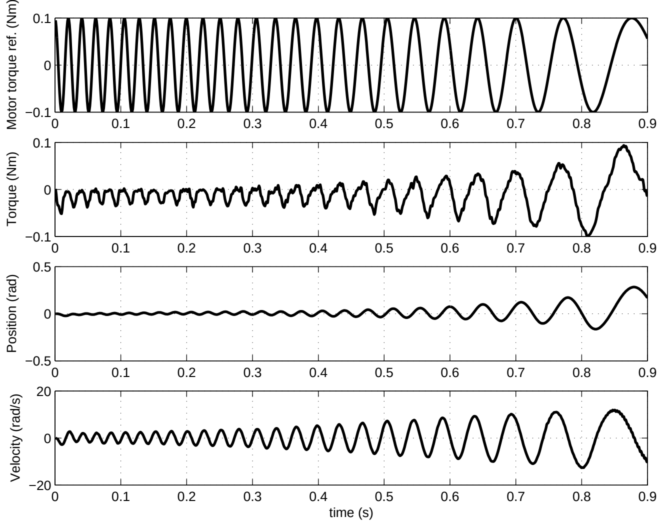

Figure 8: Input and Output data on sample test

J (kgm^2)	B (Nms/rad)	K (Nm/rad)
$1.2876 \cdot 10^{-5}$	0.0071	0.7185

Table 1: Medium values for the second order linear model

the measured and estimated velocities and positions obtained using all the models. Finally, a comparison among the performances achieved using the three proposed models is shown in Fig.15 where it is proved that increasing the order of the system from the second order to the sixth order marginally improves model fitting (Fig.15).

6 Conclusions

In this paper, three linear time-invariant lumped models of a human hand grasping a knob with three fingers are presented. These models have been employed to get an experimental identification of the system mechanical impedance. The models proposed describe the hand dynamics independently of the grip force exerted. This approach differs from that of some authors (e.g. Hajian, 1997 and Hasser,2002) who studied the effect of the grip force on the human hand mechanical impedance. As a matter of fact most haptic devices do not have a force transducer, and so the direct control of the grip force is not possible. Neglecting the grip force, obviuosly introduces some uncertainty on the model parameters, but it allows postulating the existence of a region, within the complex plan, where the Nyquist diagram of the mechanical impedance must be confined, independently on the operator or the grip force (Fig.16). This fact will allow reformulating the stability condition for haptic systems using less restrictive conditions on the operator's passivity (Colgate et al., 1994).

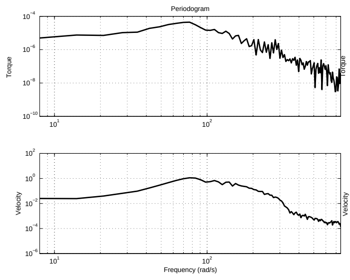

Figure 9: Data spectra

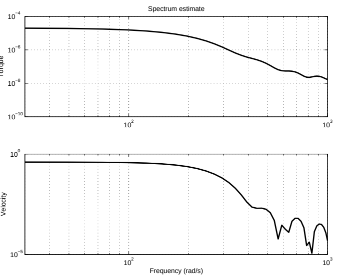

Figure 10: Spectrum Extimate

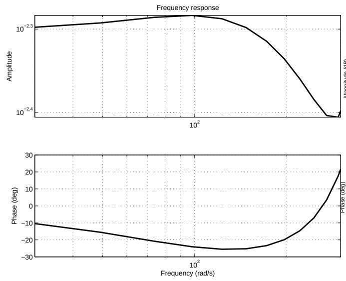

Figure 11: Experimental frequency response

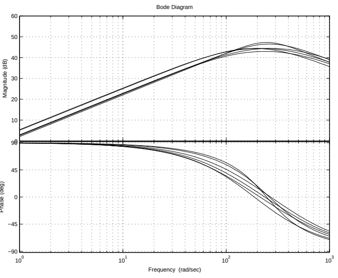

Figure 12: Second order models

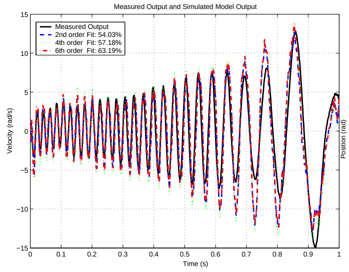

Figure 13: Measured Output and Simulated Model Output

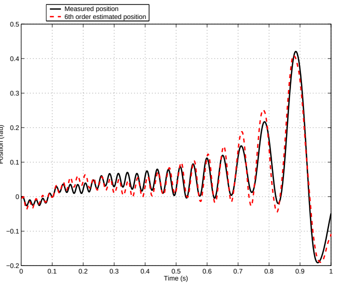

Figure 14: Measured position and simulated model position

Finally, in order to further improve the correspondence between experimental recordings and theoretical models, future work will be devoted to develop an approach identifying the human hand impedance by means of nonlinear models.

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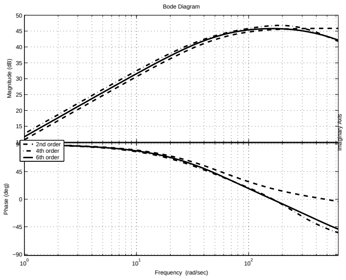

Figure 15: Bode plots of second, fourth and sixth order models

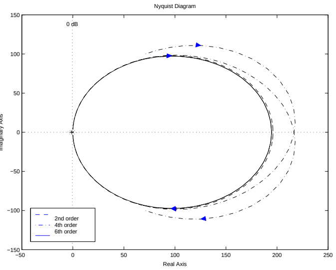

Figure 16: Nyquist plot of human hand mechanical impedance

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