

Effects of Device Coupling on Haptic Performance

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I. INTRODUCTION

At the moment, performance evaluation of force feedback haptic devices presents a huge hurdle towards the general acceptance of haptic technologies by the public. The wide range of device mechanism and uses poses a seriously challenging task of evaluating how a device will perform.

Currently we evaluate the performance of devices based on respective quantifiable performance metrics for haptic systems. These haptic systems are analysed based on the device properties in the unpowered, powered, and interactive state [[Samur12]]. Still, we lack valuable quantitative metrics that consumers could use to evaluate the quality of a device akin to the ??? for sound systems or ??? for televisions. Progress has been made to characterize the performance of specific devices based on their ability to perform in specified tasks that are fairly universal for haptic applications based on psychophysical evaluation test-beds. These widely accepted tasks can be partitioned into navigation, manipulation, and selection tasks.

Theoretically, a device's ability to perform well in these tasks should correspond to the overall usability of the device and thus, if quantified, could represent a means to discern a 'good' device from a 'bad' device. The usage of tried psychophysical evaluation techniques such as the fitts' tapping test[insert reference], peg in hole tests, etc., allow for the quantification of a device performance based on the users ability to perform a task of varying difficulty in a specified time.

These techniques have preliminarily been shown to be an effective means of evaluating two very different devices to perform a desired tasks. However, these evaluations are based on an ad hoc usage of the device workspace to perform the required tasks. In this study we seek to perform preliminary investigations into the dependency of device performance while performing the same task at different locations in the workspace.

We seek to evaluate the forces that a device may impart upon a user to decrease their ability to accomplish a simple

yet universally navigational task of moving from one area of a workspace to another along a straight line. These forces will here on out be referred to as parasitic forces. The understanding of the nature of these parasitic forces will be generalized but will be further elaborated upon for the 2D case of a planar-five-bar mechanism. Finally, simulation will be compared to experimental results for the case of the five-bar-mechanism to determine if, and then to quantify by how much, the device performance for a standard navigational task is influenced by the trajectory.

The motivation for this study is to formalize the notion of parasitic forces resulting from the manipulator dynamics that can decrease performance as well as providing a groundwork for future studies to explore the reduction of parasitic forces using redundant mechanisms. While this may actually muddy the water in terms of providing a clear-cut answer to the problem of quantifying a haptic device, it may allow for users of pre-built devices to better utilise their existing workspace to increase device performance for specific tasks.

II. THEORETICAL BACKGROUND

To better familiarize the reader with the nature of the study, here we will elaborate on the background theory required for the study.

A. Fitts' Law and the tapping test

Drawing from Claude Shannon's seminal information theory work, *Mathematical Theory of Communication*[[Shannon48]], Paul Fitts hypothesised that the time it took for a human to accomplish a task was linearly proportional to the difficulty of the task [[Fitts54]]. The relationship Fitts devised is analogous to Shannon's Theorem [[Shannon48]] and is referred to as Fitts' Law:

$$MT = \frac{ID}{IP} \quad (1)$$

Where, MT is the measured time, ID , is termed the index of difficulty and, IP , the index of performance. The index of difficulty is defined as,

$$ID = \log_2 \left(\frac{2A}{W} \right) \quad (2)$$

ID , is a way of non-dimensionalizing the difficulty of a movement task and corresponds to the ratio of the distance of an object, A , to the characteristic width of the object, W . Fitts required users tap a stylus between two targets of varying distance and size while measuring the time taken to perform the task. A linear regression was then performed on the data providing a line of best fit.

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$$MT = a + bID \quad (3)$$

The intercept, a , and slope, b , are empirically determined constants. The slope of this line, b , corresponds to the reciprocal of the Index of Performance, IP , and is assumed constant for the specific tool or device the user is operating with. The use of the base-2 logarithm in (2) allows for the ratio of distance to object width (corresponding to the associated difficulty of a task) to be expressed in units of *bits*. Rearranging equation (1) to solve for IP we see the Index of Performance, IP , can be expressed in units of $\left[\frac{\text{bits}}{\text{sec}}\right]$.

Ideally the intercept, a , is zero and deviations can be seen to indicate inaccuracies in the model though can also be attributed to by other additive effects that increase the measured time of a task but are not directly related to the task itself (i.e. button pressing to start and stop the measured time).

The Fitts' Law model of human response time as a function of task difficulty in 1D has held up well against scientific scrutiny and the results have been replicated and expanded upon for the 2D Steering Law [[insert references]] and even somewhat so for the 3D cases[[insert references]]. The validity of Fitts' Law as a tool for measuring the performance of haptic devices and virtual displays has also been demonstrated. For a more detailed introduction to the intricacies of Fitts' Law, including an attempt at a derivation of the equation from physical principals, the authors direct the reader to references [[insert citations]].

The form of Fitts' Law we will be using is referred to as Shannon's variation as it is suggested by a direct analogy with Shannon's information theorem and is expressed as:

$$MT = a + b \log_2 \left(\frac{A + W_e}{W_e} \right) \quad (4)$$

Where, W_e , is defined as the *Effective Target Width* [[Welford68]].

B. Dynamic Formulations and Representations

In order to gain insight into the role parasitic forces may have on a haptic user, we must first develop a dynamic representation of the device. This section aims to develop a generalized minimum representation for a haptic device that partitions the forces the device imparts on the user during navigation into those that exist within the *operational space* and those in an orthogonal space defined as the *admissible-motion space*. This representation is described in detail by Kovecses [[Kovecses08]].

The variational form of the system dynamics is expressed with the scalar equation:

$$\delta \hat{q}_a^T (M \dot{q}_a + c - \tau) = 0$$

Here the inertia tensor, M , centrifugal and Coriolis forces, c , and the generalized torques, τ , are represented in the joint space. The vector form of the joint space dynamics is:

$$M \dot{q}_a + c = \tau$$

The joint space velocities are mapped to the *operational* and *admissible-motion* spaces via the transformation,

$$\dot{u} = R \dot{q}_a$$

where $\dot{u} = [\dot{u}_{op} \dot{u}_{adm}]$ and $R = \begin{bmatrix} J \\ B \end{bmatrix}$. J is the *Jacobian* mapping the joint variables to the operational space coordinates. The operation space coordinates are associated with a space of constrained motion for the device end-effector. We impose that R must be invertible through the selection of the matrix B which maps the joint velocities to the admissible-motion space. This allows us to express the joint velocities as:

$$q_a = R^{-1} \dot{u}$$

The variations can then be expressed as:

$$\delta q_a = \delta u^T R^{-T}$$

The substitution of the above equation into [[insert number equation]] allows us to write the variational form of the system dynamics in terms of the operational and admissible-motion spaces.

$$\delta u^T R^{-T} (M \dot{q}_a + c - \tau) = 0$$

The vector form of the operational and admissible-motion space dynamics is then written as:

$$R^{-T} M \dot{q}_a + R^{-T} c = R^{-T} \tau$$

Differentiation of equation [[insert equation number]] leads to the acceleration level relationship:

$$\dot{q}_a = R^{-1} \ddot{u} + \dot{R}^{-1} \dot{u}$$

Substitution of the above equation into equation [[insert equation number]] leads to the device dynamics represented in the operational and admissible-motion space with the kinematic parametrizations also represented in the operations/admissible-motion space realization.

$$R^{-T} M \left(R^{-1} \ddot{u} + \dot{R}^{-1} \dot{u} \right) + R^{-T} c = R^{-T} \tau$$

Expanding the above equation permits the device dynamics to be expressed as:

$$R^{-T} M R^{-1} \ddot{u} + R^{-T} M \dot{R}^{-1} \dot{u} + R^{-T} c = R^{-T} \tau$$

Grouping the acceleration and velocity terms together we arrive at the equation:

$$R^{-T} M R^{-1} \ddot{u} + R^{-T} \bar{c} = R^{-T} \tau$$

The first term corresponds the the inertial forces felt in the operational and admissible motion spaces as a result of the device acceleration.

$$f_1 = R^{-T} M R^{-1} \ddot{u}$$

The second term corresponds to the inertial forces associated with the device velocities often called the centrifugal and Coriolis forces.

$$\mathbf{f}_2 = \mathbf{R}^{-T} \bar{\mathbf{c}}$$

The term on the right hand side of equation [[insert equation number]] corresponds to the applied forces at the haptic end-effector with respect to the operational and admissible-motion spaces.

If we define $\mathbf{W} = \mathbf{R}^{-T} \mathbf{M} \mathbf{R}^{-1}$, $\mathbf{z} = \mathbf{R}^{-T} \bar{\mathbf{c}}$, and $\mathbf{s} = \mathbf{R}^{-T} \boldsymbol{\tau}$ we can rewrite the dynamic equations as:

$$\mathbf{W} \ddot{\mathbf{u}} + \mathbf{z} = \mathbf{s}$$

This can be represented in block matrix form as:

$$\begin{bmatrix} \mathbf{W}_{op} & \mathbf{W}_{oa} \\ \mathbf{W}_{ao} & \mathbf{W}_a \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{u}}_{op} \\ \ddot{\mathbf{u}}_a \end{bmatrix} + \begin{bmatrix} \mathbf{z}_{op} \\ \mathbf{z}_a \end{bmatrix} = \begin{bmatrix} \mathbf{s}_{op} \\ \mathbf{s}_a \end{bmatrix}$$

Finally, the force that we feel in the admissible-motion space is the parasitic force that a user trying to navigate strictly in the operational space would feel for a haptic device. The dynamic equation associated with the parasitic forces is then written as:

$$\mathbf{W}_{ao} \ddot{\mathbf{u}}_{op} + \mathbf{W}_a \ddot{\mathbf{u}}_a + \mathbf{z}_a = \mathbf{s}_a$$

$$\ddot{\mathbf{u}}_a = \frac{\mathbf{s}_a - \mathbf{z}_a - \mathbf{W}_{ao} \ddot{\mathbf{u}}_{op}}{\mathbf{W}_a}$$

III. METHODS AND ASSUMPTIONS

Before you begin to format your paper, first write and save the content as a separate text file. Keep your text and graphic files separate until after the text has been formatted and styled. Do not use hard tabs, and limit use of hard returns to only one return at the end of a paragraph. Do not add any kind of pagination anywhere in the paper. Do not number text heads-the template will do that for you.

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$$\alpha + \beta = \chi \quad (1)$$

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- The abbreviation i.e. means that is, and the abbreviation e.g. means for example.

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TABLE I
AN EXAMPLE OF A TABLE

One	Two
Three	Four

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Fig. 1. Inductance of oscillation winding on amorphous magnetic core versus DC bias magnetic field

an example, write the quantity Magnetization, or Magnetization, M, not just M. If including units in the label, present them within parentheses. Do not label axes only with units. In the example, write Magnetization (A/m) or Magnetization A[m(1)], not just A/m. Do not label axes with a ratio of quantities and units. For example, write Temperature (K), not Temperature/K.

V. CONCLUSIONS

A conclusion section is not required. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions.

APPENDIX

Appendices should appear before the acknowledgment.

ACKNOWLEDGMENT

The preferred spelling of the word acknowledgment in America is without an e after the g. Avoid the stilted expression, One of us (R. B. G.) thanks . . . Instead, try R. B. G. thanks. Put sponsor acknowledgments in the unnumbered footnote on the first page.

References are important to the reader; therefore, each citation must be complete and correct. If at all possible, references should be commonly available publications.

REFERENCES

- [1] G. O. Young, Synthetic structure of industrial plastics (Book style with paper title and editor), in *Plastics*, 2nd ed. vol. 3, J. Peters, Ed. New York: McGraw-Hill, 1964, pp. 1564.
- [2] W.-K. Chen, *Linear Networks and Systems* (Book style). Belmont, CA: Wadsworth, 1993, pp. 123135.
- [3] H. Poor, *An Introduction to Signal Detection and Estimation*. New York: Springer-Verlag, 1985, ch. 4.
- [4] B. Smith, *An approach to graphs of linear forms* (Unpublished work style), unpublished.
- [5] E. H. Miller, *A note on reflector arrays* (Periodical styleAccepted for publication), *IEEE Trans. Antennas Propagat.*, to be publised.
- [6] J. Wang, *Fundamentals of erbium-doped fiber amplifiers arrays* (Periodical styleSubmitted for publication), *IEEE J. Quantum Electron.*, submitted for publication.
- [7] C. J. Kaufman, Rocky Mountain Research Lab., Boulder, CO, private communication, May 1995.
- [8] Y. Yoroazu, M. Hirano, K. Oka, and Y. Tagawa, *Electron spectroscopy studies on magneto-optical media and plastic substrate interfaces*(Translation Journals style), *IEEE Transl. J. Magn.Jpn.*, vol. 2, Aug. 1987, pp. 740741 [Dig. 9th Annu. Conf. Magnetics Japan, 1982, p. 301].
- [9] M. Young, *The Techincal Writers Handbook*. Mill Valley, CA: University Science, 1989.
- [10] J. U. Duncombe, *Infrared navigationPart I: An assessment of feasibility* (Periodical style), *IEEE Trans. Electron Devices*, vol. ED-11, pp. 3439, Jan. 1959.

- [11] S. Chen, B. Mulgrew, and P. M. Grant, A clustering technique for digital communications channel equalization using radial basis function networks, *IEEE Trans. Neural Networks*, vol. 4, pp. 570-578, July 1993.
- [12] R. W. Lucky, Automatic equalization for digital communication, *Bell Syst. Tech. J.*, vol. 44, no. 4, pp. 547-588, Apr. 1965.
- [13] S. P. Bingulac, On the compatibility of adaptive controllers (Published Conference Proceedings style), in *Proc. 4th Annu. Allerton Conf. Circuits and Systems Theory*, New York, 1994, pp. 816.
- [14] G. R. Faulhaber, Design of service systems with priority reservation, in *Conf. Rec. 1995 IEEE Int. Conf. Communications*, pp. 38.
- [15] W. D. Doyle, Magnetization reversal in films with biaxial anisotropy, in 1987 *Proc. INTERMAG Conf.*, pp. 2.2-12.2-6.
- [16] G. W. Juetten and L. E. Zeffanella, Radio noise currents in short sections on bundle conductors (Presented Conference Paper style), presented at the IEEE Summer power Meeting, Dallas, TX, June 22-27, 1990, Paper 90 SM 690-0 PWRS.
- [17] J. G. Kreifeldt, An analysis of surface-detected EMG as an amplitude-modulated noise, presented at the 1989 *Int. Conf. Medicine and Biological Engineering*, Chicago, IL.
- [18] J. Williams, Narrow-band analyzer (Thesis or Dissertation style), Ph.D. dissertation, Dept. Elect. Eng., Harvard Univ., Cambridge, MA, 1993.
- [19] N. Kawasaki, Parametric study of thermal and chemical nonequilibrium nozzle flow, M.S. thesis, Dept. Electron. Eng., Osaka Univ., Osaka, Japan, 1993.
- [20] J. P. Wilkinson, Nonlinear resonant circuit devices (Patent style), U.S. Patent 3 624 12, July 16, 1990.