PERFORMANCE MEASUREMENTS FOR ROBOTIC ACTUATORS

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Abstract
The first part of this paper present an argument on the importance of quantitative methods in robotic research. The remaining sections propose detailed performance metrics for actuator evaluation and example specifications. Several measurements which are new to actuator research are proposed: Impedance ("Backdrivability"), Force Dynamic Range and Force Fidelity. These specifications have emerged from research in robotics and haptics and address the need to obtain a more thorough understanding of machine performance.

1 “It worked once, I'll show you the video”

Robotics research has seen an increase in the complexity of the hardware used for robotic tasks. Improvements in the understanding of manipulation and machine dynamics have led to better control and sensing strategies. These strategies have driven the need for more complex hardware with greater capability across a number of areas including accuracy, degrees of freedom and power density to name a few. Despite advances in robot hardware, machines do not typically perform at the level predicted by algorithm research. Hardware limitations such as backlash, friction, saturation and quantization noise place serious limits on the performance that is realized from these systems.

One significant reason for the disparity between theory and practice is that many analytical tools break down in the presence of nonlinearities. As the number of actuators, sensors and nonlinearities in a system grows, the ability to predict system behavior diminishes. In spite of this problem, many complex robot systems are capable of performing useful tasks with some degree of success in the presence of these nonlinearities. The lack of robust, predictable performance is disappointing though, and it is tempting to save a video of the device working for two or three trials and move onto another topic.

An alternative is to use a more quantitative approach. Rather than assume that the system performance can be predicted precisely, one can start with the premise that the machine’s performance will be nonlinear and measure its performance across a number of metrics at various operating points. Once a set of metrics has been established, researchers can begin to correlate task performance with quantitative metrics. While demonstration of task performance is the final goal, a set of performance measurements describes the machine in a manner which is different from a task demonstration. This paper begins to address the issue of what kinds of quantitative measures may be useful in evaluating robotic and haptic hardware.

2 The Need For Quantitative Performance Criteria

One of the most difficult tasks faced by the users of robotic (including haptic) devices is the lack of common specifications across various devices. Many of the existing hardware designs address some subset of the imperfections in hardware systems yet it is hard to compare the various robotic systems in a quantitative way. Many of the systems are one-of-a-kind so it is not surprising that a detailed comparison of all systems does not exist. As an alternative to performing a device-to-device comparison, a set of performance metrics which evaluates performance across a large range of operating conditions would serve the users of these devices well. In particular a set of metrics which are independent of the task would be very useful. Dynamic range may be important for some tasks while force bandwidth may be important for others. When one robotic system is successful where another has failed, this set of quantitative performance metrics will help us to understand what kinds of properties are important in performing the task. Haptic devices have highlighted the inadequacy of specifications like power density or inertia when describing a robotic system. Backlash, friction and the control algorithm all have significant effects on the system’s performance. A much more detailed set of measurements is necessary.

Haptics research has demonstrated the need for actuators with exceptional dynamic range and fidelity but evaluation of haptic display devices has suffered from a lack of standards in the field. In response, several useful metrics have been proposed for the haptics community [Hayward and Astley, 1995]. In this spirit, we’d like to propose some quantitative performance metrics for actuators in haptic devices. An actuator design is presented in [Morrell, 1996, Morrell and Salisbury, 1995]. In the course of trying to quantify and compare its performance to existing actuators, several performance metrics were developed. The remainder of this paper will discuss
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Table 1: Actuator Performance Specifications

2.1 With or Without the Control System?

A fundamental issue in the measurement of robot performance arises when the designer is asked to specify performance of the system. Specifically, should the performance be specified for a passive system, independent of control law, or should a control law be included? The properties of the system which are independent of control law may be measured or determined quickly from component specifications. The properties that depend on the control law must be measured with the control law in operation. While it is tempting to avoid the control law issue when choosing an actuator, it is clear that actuator nonlinearities (e.g., friction, backlash and saturation), sensor nonlinearities (e.g., drift and quantization noise), and transmission properties (e.g., stiffness and damping) will all affect the system performance. Further, a control law which works well on one specific hardware configuration, may not work well at all when the system nonlinearities change. For example, a control law may work well at eliminating the effects of drive train friction, but may not do well at eliminating saturation effects. An undamped transmission may require active damping but the velocity sensor data may be too noisy. For these reasons, we feel the performance should be specified for the system both with and without a control law. It is recognized that the characteristics measured with the control law active are not invariant and may be improved or degraded with a change in control law. Nonetheless, the measurements are a meaningful starting point for many designers.

2.2 Operating Points

The need to specify the operating conditions for various tests was addressed in [Hayward and Astley, 1995]. Many of the differences in various systems are largely due to non-ideal effects such as friction, saturation and backlash. The amplitude of excitation as well as the operating point may have a significant effect on the frequency response data. Since the terms “large signal” and “small signal” are vague, Hayward & Astley suggest that frequency response data be taken using excitation signals of 1%, 10%, and 100% of full scale. This specification is sound and is reiterated in this paper. The selection of operating point will be the center of the workspace (position or force) and specifications for best and worst case are also included.

2.3 Example Actuator

As was mentioned earlier, the goal of this paper is to provide a complete and well defined set of performance metrics which clearly display actuator performance. To generate the example data, an actuator with torque saturation, position saturation, finite sampling effects, quantization noise and a friction was simulated.

Simulation was chosen over the existing experimental data in [Morrell, 1996] in order to provide a clear and consistent set of data for this paper. It is acknowledged that experimental data are preferable, but not central to the message of this paper.

The metrics proposed here will generally be for a single degree of freedom system. Additional degrees of freedom will increase the number of possible operating conditions and therefore the number of tests. The metrics proposed here should be performed for multiple axes especially when the device has non-isotropic characteristics.

Table 2 displays the results of the simulated measurements on the example actuator.

3 Quasi-Static Properties of the Actuator and Sensors

Quasi-static properties of the actuator and sensors are those properties which affect the behavior of the system when it is nearly stationary. They are not affected by the
Peak Force, STPKF (1 msec)
Peak Force, PTPKF (10 msec)
Peak Force, LTPKF (continuous, no cooling)
Peak Force (continuous, N₂ cooling)
Position Resolution
Force Resolution
Position Range
Peak Acceleration
Position Precision
Force Precision
Force Dynamic Range
Position Bandwidth - Impedance Control w/ Force Feedback
X̄des = 1% of position range
X̄des = 10% of position range
X̄des = 100% of position range
Force Bandwidth - Integral Force Control
F̄des = 1% of force range
F̄des = 10% of force range
F̄des = 100% of force range
Force Fidelity Bandwidth - Integral Force Control (Distortion < 5%)
F̄des = 1% of force range
F̄des = 10% of force range
F̄des = 100% of force range
Minimum Impedance - Integral Force Control, F̄des = 0
X̄des = 1% of position range
X̄des = 10% of position range
X̄des = 100% of Position range
Impedance Bandwidth - Integral Force Control, F̄des = 0
X̄des = 1% of position range
X̄des = 10% of position range
X̄des = 100% of Position range

Table 2: Summary of Performance Measurements

Measured at Center of Workspace
8000 mNm
6000 mNm
800 mNm
2000 mNm
0.1 degrees
0.1 mNm
+/ - 4.5 rads
0.23 rad/sec
1.2 degrees (0.2% of workspace)
2.5 mNm (0.3% LTPKF)
320:1

choice of control law. In [Hayward and Astley, 1995] both quasi-static and dynamic properties of the actuators and sensors are labeled "Gross Features."

3.1 Peak Force (Transient & Continuous)
A transient peak force measurement is useful for determining short term capacity of an actuator and the following metrics are proposed in [Hayward and Astley, 1995]: 1 msec (Short Transient Peak Force - STPKF) and 10 msec (Persistent Transient Peak Force - PTPKF). If the actuator performance is such that these tests are misleading, the onus is on the actuator manufacturer to specify peak force for multiple durations in order to clarify the response. For example, many actuators may not be able to generate peak force in 1 msec.

For continuous peak force (Long Term Peak Force - LTPKF), the number should reflect the steady state force of the actuator at the output. Usually this specification is limited by heat dissipation. As a result, any special cooling requirements should be included in the specification.

3.2 Position & Force Resolution
Position resolution is the minimum absolute resolution of the position sensing on the device in units of displacement at the output point (not %). If no position sensor exists, then this number should be specified as N/A. If the resolution changes throughout the workspace, then this relationship should also be included. A thorough specification would include an equation or graph for resolution in the workspace such as:

\[ \text{Resolution} = f(\theta_1, \theta_2, \theta_3) \]

Force resolution is the minimum absolute resolution of the force sensor on the device in units of force at the output point (not %). If no force sensor exists, then this number should be specified as N/A.

3.3 Position Range (Workspace)
Most robotic systems have limitations on the range of motion and this number is generally easy to quantify. For multi-DOF systems, the range in each dimension should be specified. Specification in both joint space and Cartesian space may be useful to the end user.

4 Dynamic Properties of the Actuator and Sensors
Dynamic properties of the actuator and sensors are those properties which affect the system performance when the actuator is in motion, but are not affected by the choice of control law.
4.1 Unpowered Impedance

Actuator impedance is extremely important when the robot and the environment it contacts are in motion. Designers refer to "backdrivability" and "compliance" to describe the relationship between force and displacement of the actuator. Frequently, backdrivability is used to describe the friction that is sensed when a force is applied to the output of a haptic device and compliance refers to the stiffness that is sensed. "Reflected Inertia" refers to the inertia of the device at the output. Impedance encompasses all of these ideas and refers to the force/displacement relationship regardless of its cause. In tasks such as surface following or dynamic contact sensing the actuator may be required to maintain constant force in the presence of small disturbances, whether the disturbances are due to small changes in position or unmodelled contact forces.

\[
\frac{F_{\text{error}}}{X_{\text{in}}} = \omega
\]

Figure 1: Impedance response is a frequency response measurement which is obtained by measuring the endpoint force as the endpoint is moved.

The dynamic equation for a second order system, \( F(s) = (Ms^2 + Bs + K)X(s) \), may be used to model the impedance of the uncontrolled device at the output link. If the impedance is a function of kinematics, then an operating point in the workspace should be specified. This measurement is most easily accomplished by attaching the endpoint to a sinusoidal position disturbance and measuring the force applied to the output link as a function of frequency.

**Impedance Response**: The frequency response (transfer function) of the system to a position disturbance at the endpoint, i.e. the endpoint is connected to a position source:

\[
Z(\omega) = \frac{F(\omega)}{X_{\text{in}}(\omega)} \bigg|_{u=0}
\]  

(1)

where

- \( F \) = the force applied to the endpoint
- \( X_{\text{in}} \) = the position disturbance

Impedance is best thought of as the forces that result from a position disturbance. An ideal system would produce a frequency response that mimics a point mass. With viscous and coulomb friction, backlash and non-rigid transmissions, the impedance will typically take on some minimum value (determined by friction, etc.) and will increase with frequency. An [An, 1986] performed an experiment in which a robot link was placed on a moving cam, and given constant force command and force errors were measured. Figure 1 depicts this experiment. We propose a similar approach in which a frequency response measurement is performed and the impedance, \( F(s)/X(s) \), is displayed as a function of frequency. Figure 2 displays the simulated actuator impedance. The disturbance may be created with a bidirectional drive system such as a very stiff PID controlled servo attached to the output point.

\[
\text{Figure 2: Example of Unpowered Impedance, } Z(\omega), \text{ at 0.1%, 1%, 10%, and 100% of displacement range. The constant impedance section is the caused by the quantization of the force sensor and friction.}
\]

As mentioned above, the choice of operating point is important. Performing frequency response measurements at all operating points would be ideal but is unrealistic for most systems; at a minimum specification of the testing configurations is required. If the frequency response graph consumes too much space, two scalar numbers may be specified instead, minimum impedance and impedance bandwidth. These numbers will provide a crude indication of fundamental structural frequency of the system.

4.2 Maximum Acceleration at zero velocity (peak force/inertia)

In the presence of no viscous damping or coulomb friction, many actuators can be modeled as a single mass and the maximum acceleration can be computed from the peak torque and the inertia. In the case where the damping and friction are non-zero, maximum acceleration may be mea-
sured by applying peak torque (both transient and continuous) and measuring the resulting acceleration. Since the workspace dependencies for force and impedance (mass) may not be the same, this quantity should be measured, rather than calculated from the quantities above.

5 Quasi-Static Properties of the Controlled System

Quasi-static properties of the controlled system are those properties which may be measured when it is quasi-static and are also dependent on the choice of control law. While the performance metrics should provide all the necessary information to understand the actuator, the control law architecture and gains should also be specified when presenting actuator performance data so that the performance may be reproduced easily. Since the focus of this paper is the definition of performance metrics, not a report on a specific actuator, the control law information for the example actuator will be omitted in the interest of saving space.

5.1 Force & Position Precision

Force precision is the error in force when a steady state force is commanded. This measurement should be expressed both as a percentage of continuous peak force and in units of force. The choice of control has a clear effect on this specification. For example, if a torque sensor is used to provide closed-loop feedback, the force precision may be considerably better than using open-loop torque commands.

Position precision is the steady state position error. As with force precision, this quantity should be measured both as a percentage of the actuator system workspace and in units of position. Again, a PID position control loop may provide very different response than force-feedback impedance control architecture so the control law must be included in the specification.

5.2 Force Dynamic Range

Force Dynamic Range is ratio of the maximum controllable force to the minimum controllable force. Research on haptic displays suggests that the dynamic range of force plays an important role in creating a high fidelity display [Tan et al., 1994, Rosenberg and Adelstein, 1993].

6 Dynamic Properties of the Controlled System

Dynamic properties of the controlled system are those properties which may only be measured when the system is in motion.

6.1 Position Bandwidth

Position response is the frequency response of the system to a sinusoidal position command while in free space. More specifically,

\[ H_{pos}(\omega) = \frac{X(\omega)}{X_{des}(\omega)} \bigg|_{F_e=0} \] (2)

where

- \( X_{des} \) = the desired position
- \( X \) = the actual position

This is a relatively common performance specification. The bandwidth is easily defined as the frequency at which the response function, \( H_{pos} \), is attenuated by 3 decibels. Figure 3 shows typical data for this measurement.

Figure 3: Position Bandwidth of example actuator using an impedance controller at 0.1%, 1%, 10%, and 100% of displacement range.

6.2 Force Bandwidth

Force control bandwidth is the response of the system to sinusoidal force command with the endpoint stationary. Figure 4 depicts this experiment.

Figure 4: Force control response is a frequency response measurement which is obtained with a fixed endpoint. The 3db point may be used to define force bandwidth.

Mathematically, this test is described as follows:

\[ H_f(\omega) = \frac{F_e(\omega)}{F_{des}(\omega)} \bigg|_{X_e=0} \] (3)

where

- \( F_{des} \) = the desired force
- \( F_e \) = the force exerted on the environment
$X_e = \text{the position of the end effector}$

![Figure 5: Force Bandwidth at 1%, 10%, and 100% of $L\Sigma$](image)

This specification comes from the desire to quantify a robot's performance in quasi-static applications like slow manipulation or the control of a slipping object. In this case, the ability to modulate forces applied to a relatively motionless environment is of premium importance. Force control bandwidth, $\omega_{fc}$, may be defined as the 3db point of the magnitude response of $H_f(\omega)$. Figure 5 displays this data.

6.3 Impedance (Backdrivability)

A good controller can reduce the impedance of a robotic system and the impedance of the actively controlled system should also be measured. In pure force control an ideal actuator would present zero impedance across all frequencies; in real systems this quantity should be as small as possible. As described earlier in the section on passive impedance, the system should be connected to a position disturbance and the corresponding forces should be measured.

For this case,

$$Z(\omega) = \frac{F_{\text{error}}(\omega)}{X_{\text{in}}(\omega)} \bigg|_{F_{\text{des}} = \text{constant}}$$ (4)

In this case, the desired force should typically be commanded to be zero. Impedances can be measured at 1%, 10% and 100% of the displacement range of the device. Additional measurements of the impedance with nonzero desired force may also prove useful if there is a load dependent effect such as backlash. Figure 6 shows data from the impedance response tests.

![Figure 6: Impedance (Backdrivability), $Z(\omega)$, for example actuator at 0.1%, 1%, 10%, and 100% of displacement range. Impedance bandwidth may defined as the frequency where the force error begins to increase with frequency.](image)

6.4 Force Fidelity

Force fidelity is an important, but often overlooked specification in robot actuator design. As interest in haptic interfaces has grown, it has become clear that human perception of force fidelity is quite good and that distortion of force signals in haptic display systems is undesirable. Figure 7 shows an example of several distorted force signals. The variation from a true sinusoidal signal may be measured in the least squares sense by computing the RMS error from a best fit sinusoid at the excitation frequency, $\omega$:

Given a sequence of samples, $T$, a sinusoidal curve may be fit to the data using the equation:

$$RA = T$$ (5)

where

$T = \text{sampled signal}$

$R = [\sin(\omega t) \cos(\omega t)]$

$A = [c_1 c_2]^T$

The matrix, $R$, is a two column matrix with sine and cosine values at the same frequency as the input signal to the system.

Solving the equation for the least squares minimum error,

$$A = (R^T R)^{-1} R^T T$$ (6)
A normalized measure of force fidelity is:

$$\text{Force Fidelity} = \frac{T^T H A}{T^T T}$$  \hspace{1cm} (7)

The value of this matrix expression is 1.0 for a perfect sinusoid. A value of 0.99 represents 1.0% distortion.

In this metric, the fidelity is represented as a percentage of the force magnitude. For most systems, the fidelity at large amplitudes will be much higher than the fidelity at small amplitudes where friction, backlash and quantization will limit accuracy.

Figure 8 shows the force fidelity data for the simulated actuator. For systems with backlash, the mean force can have a dramatic effect on force fidelity because the system's force distortion will vary significantly with load. Force fidelity measurements should be performed at various loads to make this fact explicit.

7 Conclusions

As task complexity has increased, so has the need for better performance measures in the haptic community. We propose that actuator performance should be measured and quantified along a number of dimensions which describe the device properties in passive and dynamic situations.

This paper presents a number of quantitative performance measures for the evaluation of actuators, robots and haptic interfaces. Some of the metrics presented here have been used in previous literature and they defined here for completeness. Measurements of Impedance, Force Distortion and Force Dynamic Range are new to the area of robot actuator performance and are important characteristics for haptic and robotic devices.

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References


