

System for performance measures of predictive grip in a dynamic haptic environment.

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Abstract Virtual environments provide a powerful means of experimentally examining object manipulation. In object manipulation a key issue is the coordination of grip force used to stabilize the object in the presence of load force variation, such as those due to inertia during object movement⁵. Here we describe the engineering of an application in which the SensAble PHANToM is used to robotically control a hand held object and provide temporally modulated force fields that can be varied on a trial-by-trial basis. Visual display is synchronized with haptic display^{1,10} and the recording of the robotic end-effector's position. Analog data from two load cells mounted on the end-effector capture the forces and torques generated during interaction with the varying force fields. The system is currently being used to study the learning of novel load force functions during object manipulation.

1 Introduction

In haptic applications, a 'virtual object' typically refers to the use of a haptic display device to provide force feedback to the tip of one finger in a way that simulates the properties of the surface of the object in contact with the finger. Thus, a device, such as the PHANToM 1.5 3 DOF robotic manipulator⁸ (SensAble Technologies) allows the finger to be placed in a thimble which transmits the force feedback which can then be used to explore virtual objects of varying shape whose compliance is determined by the force normal to the virtual surface. Surface friction effects may be varied by modulating the force tangential to the surface in relation to the normal force².

When we hold a real object between opposed finger and thumb, grip force normal to the object surfaces is precisely tuned to the load force tangential to the surfaces, which is generated by the object weight, and to the surface friction⁷. If we move a grasped object then the load force acting on the fingers depends on its mass and the acceleration induced by the arm. In this situation, grip force is also finely adjusted to the load^{5,9}. In this paper we show how the PHANToM thimble may be replaced by an instrumented manipulandum which, when grasped between finger and thumb, can be used to introduce novel load forces, enabling an examination of motor learning during object manipulation.

Research in our lab is directed at two questions of theoretical importance in motor control. The first question is whether externally generated load force perturbations

with a regular temporal pattern can be predicted as accurately as self-generated load forces¹? We describe how the PHANToM can be used to impose spatially-homogenous, sinusoidally-varying load force, at the same time as it is used to probe the subject's performance. One example of such a probe is the unexpected withholding of load force to determine whether grip force is nonetheless modulated on the basis of the predicted load¹⁰. To this end the application we describe allows the inclusion of 'catch' periods in which no force updates occur. The second question that we are addressing in our lab is whether the addition of supplementary sensory cues during imposed load force variation can aid the development of its prediction? Such cues can be introduced in the application we describe at various points during the imposed load force function. They can include brief tangential force events presented normally to the imposed load, visual functions provided via the PC monitor and auditory cues in the form of beeps or clicks.

In the following we first present the engineering aims then describe their implementation in terms of mechanical, electrical and software systems. We conclude with an example of the systems output and consider future design revisions.

2 Aims

1. Precise synchronization and control of spatio-temporal parameters over visual and haptic displays
2. Independent control of graphic and haptic software sub-systems allowing for introduction of controlled inconsistencies between haptic and visual stimuli.
3. Simultaneous data acquisition (DAQ) of multiple analog load cell signals alongside approximate force and position output from the PHANToM.
4. Easy set up for different modes of experimental control. Allowing users with minimal programming skill to rapidly implement an application.

3 Mechanical Implementation

3.1 Basic PHANToM Concept

By using a system of cables and levers the mechanics of the PHANToM transforms torques generated by three motors into three axes of orthogonal force presented to the device's end-effector (a thimble is provided as standard). The angle of each motor is recorded via an optical encoder mounted directly to its drive shaft, binary information from these encoders is used in combination with a model of the device's geometry to provide an estimate of the end-effector position relative to an initially calibrated origin. In this manner it is possible to resolve the PHANToM's position in Cartesian form with a resolution of 0.03mm at the centre of its workspace. Overall control of motor torque output with relation to encoder position is conducted using a software control algorithm continuously executed at high speed, referred to by the manufacturer as the "Servo Loop"⁸.

3.2 Force and Torque Measurement

PHANToM force output is controlled in open-loop manner. In order to measure the load force applied to the end-effector, as well as the grip force applied by the subject, the thimble is replaced with the instrumented manipulandum shown in Figure 1. This comprises two miniature 6-DOF load cells (ATI nano 17) in a dumbbell configuration³ enabling the collection of the twelve axis of forces and torque (F/T) generated during manipulation of the end-effector using a thumb and fore-finger precision grip. Exchangeable contact surfaces on the grip plates enable the frictional properties of the grasp surface to be easily altered.

The primary requirement influencing the selection of the load cells was the need for full 6DoF to successfully resolve load and grip forces involved in

the interaction, derived from F_x , F_y and F_z components. Torque information T_x and T_y is used in calculation of centre of pressure of the applied grip, T_z monitors torques which can occur due to the currently fixed orientation of the load cell at the end-effector. Other factors influencing the choice included small size, which affords a stable and comfortable grip, and low weight, which minimises changes to the PHANToM's inertia, balance and motor load. Resolution is also a factor to be considered, Manufacturer quoted resolution for the Nano17 is: 1/320N F_x and F_y , 1/640N F_z , 1/128Nmm T_x - z .

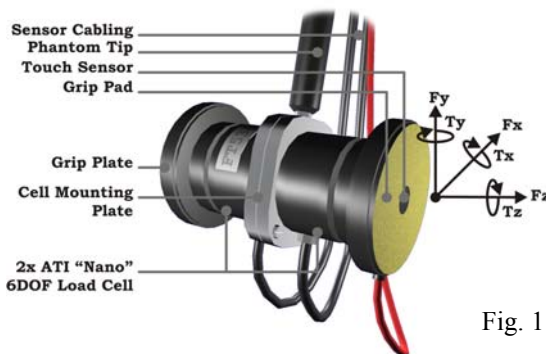


Fig. 1

4 Electrical Implementation

4.1 Acquisition Hardware

Raw strain gauge signals from the two 6 DOF load cells are provided via twelve pairs of +/-5V calibrated Differential Output lines. To facilitate acquisition of these signals, in combination with the position information provided by the phantom, a National Instruments PCI-MIO board coupled to a BNC-2090 breakout box is used. As this board only offers a standard 16 channels of analogue input, it is necessary to forgo the usual differential output of the load cell amplifiers and construct appropriate cabling for single ended non-referenced operation. Load cell data is stored and handled by the program in raw binary form, calibration and bias of the loadcell strain gauge signals as well as their decoupling into F/T vectors is performed in the analysis stage.

4.2 Acquisition Performance

A problem presented by the combined Control/acquisition system is that the CPU of the host machine is already fairly heavily loaded in maintaining continual updates of

the graphics display and PHANToM Servo Loop. To avoid potentially destabilizing this by adding a 250 Hz 12 Channel synchronous data acquisition operation, it is necessary to use the DAQ Board in an Asynchronous DMA based mode, allowing acquisition to be performed with virtually no CPU resource overhead. The trade off in running an operation asynchronously to the CPU is that online access to the acquired data during the main program loop is made difficult.

Maximum data capture time is currently limited to around 20 seconds, as resource restrictions also prohibit the use of buffering techniques during the trial. Problems are also presented in temporal synchronization of the resultant F/T and PHANToM position data streams. This is currently solved by extensive time stamping of events, allowing data streams to be aligned and interpolated in analysis.

4.3 Device Protection

As well as providing force measurement, it is necessary to have adequate protection for the equipment from exposure to excessive forces should the subject accidentally release the manipulandum. As the PHANToM's usual software cut outs may prove inadequate in this particular application, a retro-reflective optical touch sensor mounted in the grip surface is wired in place of the PHANToM's remote motor enable switch. A custom-built controller box supplies power to the optical sensor and provides a "trip" function; following a period of 100ms during which the subjects fingers are more than a few mm away from the grip plate, force production ceases until the sensor is manually reset by the experimenter.

5 Software Implementation

5.1 Application Framework

The software development in this experiment was conducted under MS Visual C 6 and based around SensAble's HapticView framework, the resultant application runs under XP Pro on a standard 2GHz P4 desktop PC. HapticView was used due to the improved low level control it provides through separation of the graphics and Servo Loops, something that GHOST alone and its associated graphics manager make difficult to implement in a predictable manner, an important factor when the visual display bears little relation to the forces rendered by the PHANToM. This improved control is realized through the provision of a set of basic template functions, facilitating handling of device and display initialization, timing and so forth in a easily accessible manner. HapticView allows the programmer to spend more of the development cycle tailoring the application to the projects actual requirements and less time dealing with the complexities of integrating it's various sub systems (Haptics, graphics, data acquisition etc.) while simultaneously keeping code complexity to a minimum. In addition, due to its open source origins, should low level modification to the framework become necessary it can be easily implemented. due to availability of complete source code. In this case, HapticView is used to simplify integration of

SensAble’s GHOST API, the popular Graphics API OpenGL and National Instruments’ NIDAQ data acquisition libraries.

The final structure of the resultant application, from initiation to termination, is outlined in the flow diagram shown in figure 2. The three main execution tracks of the program are detailed, Graphics loop, Servo Loop, and DAQ Operations. Master timing of all operations in the program, apart from Asynchronous DAQ operation, is implemented by calls to the systems internal performance counter⁶ Although this does not provide completely deterministic performance, a drawback of most multi-tasking OSs, it does allow for very precise measurements of when relevant system events occur and hence detection and assessment of errors in the output data.

After the basic program and device initialization, the majority of the application’s function is gov-

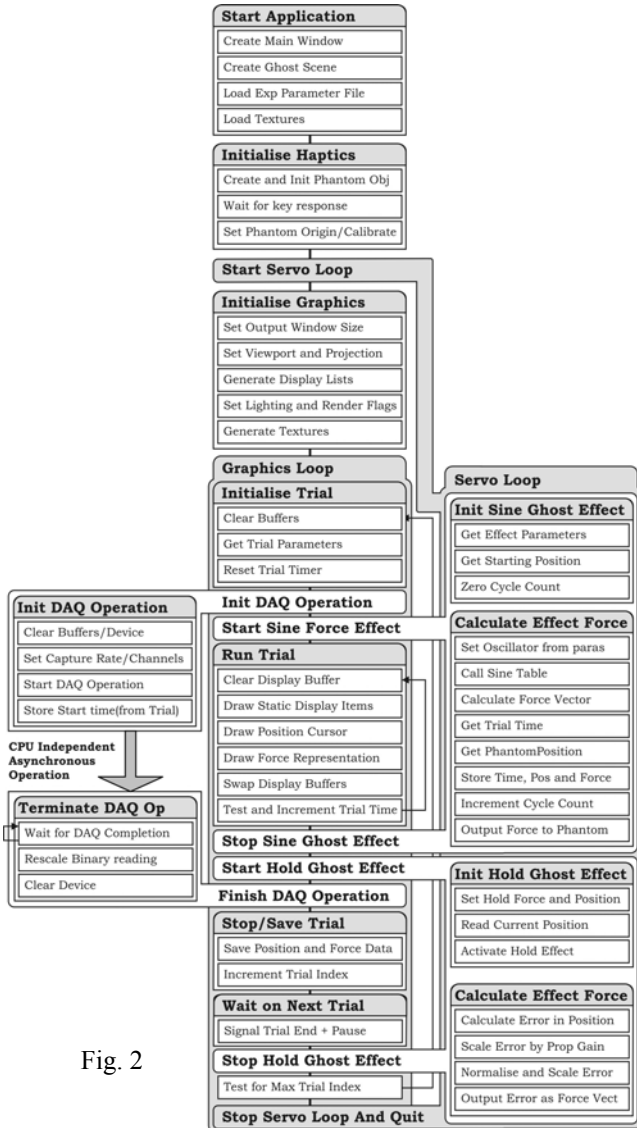


Fig. 2

erned by code in the graphics loop. This loop sets the structure and timing of trials dictated by parameters read in from external files (such as the characteristics of the force field and nature of cues discussed below), running the DAQ operation and switching between force effects. The graphics loop also handles redrawing of the OpenGL display buffer. This is shown in greater detail in the figure.

5.2 Force Effects

All the force profiles required for this experiment are achieved using two ‘Ghost effects’ modified from SensAble’s GstEffect base class; Sine and Position Hold. These can be added and removed from the path of the Servo Loop during the experiments progress, closing the loop between time and position values and the PHANToMs force output.

The Sine effect is responsible for generating time dependent sinusoidal forces with amplitude between 1 and 5N along a single axis of the device. Different values of frequency and phase, relative to the visual display, are also supported by the effect. Typical values for these parameters during preliminary trials and tests are 0.5- 2Hz and 0-90 degrees respectively. Provision is also made in this effect for discontinuities in the force function. This feature is used in the ‘catch’ trials where the force update is momentarily suspended.

The sine function used in the servo and graphics loop is based upon linear interpolation between elements of a half sine lookup table with 0.1 degree increments and 16-bit resolution. Although this leads to some distortion of the function, it appears to be more than adequate for this apparatus/experiment and presents a considerable performance increase over standard floating-point sine implementations allowing for complex waveform generation through additive synthesis. It is also possible for other arbitrary waveforms to be substituted for the sinusoid via an external file.

The position holding effect applies proportional gain to the positional error to produce a force that holds the PHANToM steady in its current position during the rest periods between trials.

During preliminary performance tests it was found that in this application the Phantom Servo Loops execution period was at maximum 2.7ms and minimum 29uS. However, Ghosts internal compensation algorithm ensures that on average the system cycles at least once per millisecond (ie. 1kHz). Temporal stability in this aspect is vital to maintain accurate force rendering and prevent control loop instability.

5.3 Visual Display

OpenGL is the graphics API used to generate the experiment’s visual stimulus. Selected because it is already heavily integrated into SensAble’s GHOST API, and also because of its well known support and versatility over a variety of platforms and hardware implementations. Additionally, previous grip force work involving the PHANToM has relied on OpenGL for presentation of visual stimulus^{4,10} as well as amount of other work within the lab, therefore familiarity also played an important part in it’s choice..

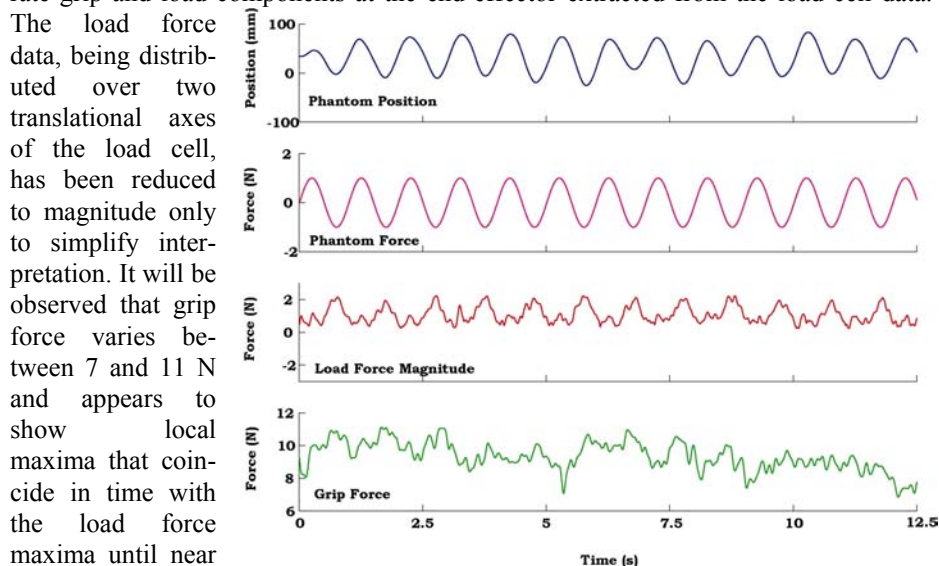
The feedback display presented to the subject in the preliminary experiments consists of two horizontal bars indicating the floor and ceiling of the subject’s movement which they should attempt to keep the end-effector within. Two spherical cursors are also provided whose vertical positions represent actual end effector position and target position. Additionally a central rectangular target zone is placed in the centre of the display. During the course of the experiment the subject is asked to either track the target cursor using the position cursor or attempt to hold the position cursor within the target zone while subjected to external perturbations. Size of the visual

display is adjusted to provide a 1:1 scale of motions made by the end-effector to distances portrayed on the monitor.

In performance measures the latency of the graphics system was at worst 48ms and at best 46ms, averaging 21.3fps over all conditions. Ideally a frame rate somewhat closer to the refresh of the monitor and synchronization with vertical blanking of the display would be desirable in future.

6 Example Output

Shown below is an example graph for a single 12 s ‘tracking’ trial. Force output at the phantom tip is a 1Hz sinusoid with amplitude 3N pk-pk. Parameters shown are y-axis position of the end-effector, approximate Servo Loop output force plus the separate grip and load components at the end-effector extracted from the load cell data.



The load force data, being distributed over two translational axes of the load cell, has been reduced to magnitude only to simplify interpretation. It will be observed that grip force varies between 7 and 11 N and appears to show local maxima that coincide in time with the load force maxima until near the end of the trial. The results of more extended psychophysical tests will be evaluated using cross-correlational techniques to determine the exact degree of correspondence between grip force and load force and the extent to which there may be said to be anticipation of the load force by the grip force.

7 Summary and Future Developments

In this paper we have presented an environment integrating several useful tools for the development of haptic research projects. Further improvements to this system may include the use of DirectX components to provide precision timed audio stimulus for future studies. Other means of cueing the subject may also become desirable at a later date, The provision of cutaneous information for example, via Piezo actuator or electrostimulator. Synchronous F/T data acquisition is an additional aim, possibly directly with the Servo Loop, to allow the development of closed loop force control applications as well as runtime analysis of subject performance.

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