A General Purpose Control-Based Trajectory Playback for Force-Feedback Systems

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Abstract

This paper describes a trajectory playback algorithm for active force-feedback devices, which extends the bead pathway metaphor to include a PID controller, to minimise error, even when the device undergoes significant disturbances. A study is presented testing the algorithm with the Phantom Omni device, under a number of different conditions simulating potential real-world use. The results show that the algorithm copes well under the conditions tested. This technique is widely applicable to playback situations (for example virtual training environments), and can be adapted to many haptic devices. As such, an open source trajectory playback library using these techniques has been developed and made available.

Keywords: haptic, control, trajectory playback, PID

1 Introduction and Background

Computer users rely heavily on visual feedback when interacting with a computer. Text and images can be used to quickly and easily display a large amount of information to users in a form that is easy to comprehend. There are some types of information however that are difficult to display through a computer monitor or even describe through words. There are many situations where being able to communicate a shape or trajectory to the user is a useful feature for a computer environment.

Tasks that require some form of manual dexterity, or that require a user to learn a series of movements or a procedure are often best learned through experience. It is not always possible to get the required level experience in the real life task. One well established area in which simulation has played an important part in training for many years is in pilot training. Trainee pilots can practice their skills in extremely realistic circumstances without any risk to themselves. Medical simulation is one example where haptic virtual environments are becoming an increasing reality for training. Doctors and veterinarians can first practice their skills in a virtual setting without risk to a patient. Even in these instances, training is one-to-one and can be restricted if no teacher is available to guide the learner. Trajectory playback is one technique that could be used to allow the system to provide trajectory information to a learner with no teacher present.

1.1 Training Applications

There is a growing body of work examining the potential of haptic virtual environments to provide training to a user in some complex task. Here haptic trajectory playback is used to allow the user to experience the movements in a three dimensional manner either through haptics alone or in combination with vision. Feygin et al. [4] conduct a study into the possibility of providing gesture training using either visual, haptic, or visual-haptic guidance. Results showed significant improvement in recreating the gesture in all conditions between the first and the last gesture. The haptic only training mode performed significantly worse than the haptic-visual training mode, but not significantly worse than the visual training mode.

Dang et al. [3] discusses a constraint-based training system that provides guidance to users by restricting their movements from deviating from a path. This method allows a user to follow the path taken for a procedure by an expert, but allows the user to apply the forces to perform the surgery. Yokokohji et al. [9] similarly examine haptic trajectory playback for the purposes of training for simple task. The system they studied actively dragged a user through a task to provide learning in performing that task. Similar techniques have also been applied to teaching Chinese handwriting. Teo et al. [7] demonstrate a system where the position of a teacher can be recorded and played back to a student to aid in forming characters. Williams et al. [8] describe a medical simulator training system for back palpation. This work compared user performance in following a trajectory when being dragged though a path with a force playback algorithm (with other virtual objects removed from the scene), with error when following a graphical representation of the path. This study showed that performance improved and error from the ideal path decreased as the user practiced the path more. Error was also less in the trajectory playback condition.

1.2 Other Applications

Training is the main application area for this technology, however there are examples in the literature of other uses; for example Gentry et al. [5] demonstrate a system which allows the user and computer to collaborate on a dancing task. Here, the user had to synchronise their moves to music and the movements of the device. The user moves in clockwise or anti-clockwise circles with the device applying a weak guiding force through the trajectory.

Haptic communication has similarly been shown to benefit users in tasks that involve more than one user in the same environment. Work by Oakley [6] examined the incorporation of haptic effects into a collaborative drawing environment to increasing awareness of other users in the environment. This work included functionality that allowed one user to drag another through a path or towards a certain point. In many shared tasks, the potential to directly interact with the other user is a powerful tool.

In situations where visual display is not an option (such as when considering accessible systems for visually impaired users) haptics can again to some extent replace the visual sense. Screen readers have proved to be a successful solution for accessing the textual information required to interact with a computer. However, this information is generally accessible only in a linear manner (from the top left corner of the screen) and non-text information such as pictures and diagrams are not easily displayed in this manner. Haptic

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playback can be used either in a single user or collaborative environment to alert the user to areas of interest or shapes and contours.

The above applications provide implementations of trajectory playback or constraint-based algorithms for one specific context of use only. Here we describe the initial implementation and evaluation of a general purpose playback library that is freely downloadable and does not limit the user to one specific device.

2 Algorithm

2.1 Bead Pathway

The playback algorithm described in this paper is based on the bead pathway model developed in [1]. This was developed for rehabilitation therapy to move the user's hand through a smooth trajectory. The pathways in this study were defined by a spline curve passing through a series of points. The user is pulled along by a spring damper system, with one end of the spring attached to a bead that is constrained to and travels along this path.

In this paper, the bead pathway model is extended by replacing the spring damper system with a PID (proportional-integral-derivative) controller. The benefits of this approach are potential for lower error and better adaptability to changes in conditions. For this work, the bead is only permitted to progress when the total error between device position and bead position is less than some threshold (the progression threshold). This guarantees that if the user resists the movement the playback is also held, maintaining the shape of the path.

2.2 PID Control

The purpose of any controller is to minimize the difference between the current value of some system and target reference system. This difference is referred to as the error. Control is performed by feeding the error back through the system in some manner (a negative feedback loop). Simple propotional control simply applys a multiple of the error to the output actuators. In a force-based system, this is similar to the operation of a Hooke law spring – force is propotional to the deviation from the set point.

The PID (see [2]) controller is a widely used control algorithm in industrial situations, which has been used in various forms for many years. Its popularity stems from the ease of implementation of a PID controller and its effective performance in a wide range of control problems. A huge range of more sophisticated control methods are available, many of which have much more accurate modelling of the dynamics of the process to be controlled, but the simplicity and effectiveness of PID control makes it a more attractive option in many cases. One similar implementation is given in [8] who used a trajectory playback PD controller for medical simulator training.

The controller extends proportional control by including the integral and derivative of the error into the output term. The integral term serves to drive the error of the system to zero; constant offsets are eliminated. The derivative term increases the response time of the system and reduces overshooting of the reference. In combination, the controller can quickly acquire a new reference value accurately without excessive oscillation. The basic structure of a PID controller is shown in Figure 1. PID controllers generally require tuning for optimal performance for a given system. Suboptimal settings lead to to sluggish response or highly oscillatory acquisition patterns.

In the implemented system, the PID controller is as used a direct replacement for the spring damper system in the bead pathway algorithm. The controller's reference value is given by the bead moving along the pathway. The pathway here is defined by linear interpolation between a sequence of sample points along the proposed trajectory. These points are user-defined; they can either be generated via some function (as in the test cases here), or they can be pre-recorded. This sampling rate is user adjustable.

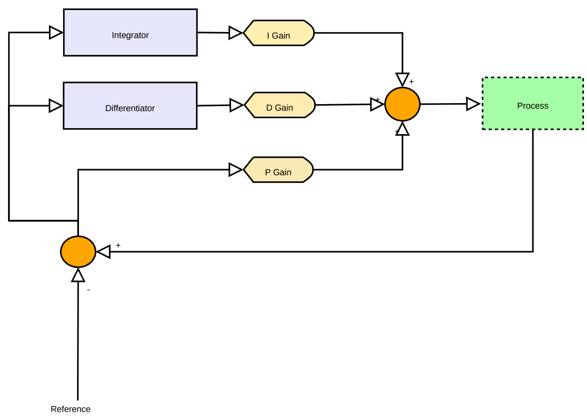

Figure 1: Block diagram of the PID controller.

2.2.1 System Tuning

There are number of standard PID control parameters which can be adjusted in this prototype. The PID controller can be tuned using standard methods. This tuning is only required for new hardware configurations, with the controller adapting to other changes in the environment automatically. In the work described in this paper, the parameters were iteratively adjusted to obtain optimal control properties for the Phantom Omni. This required only a few interations, following the standard PID tuning heuristics.

3 Experiment

3.1 Methodology

3.1.1 Test Hardware

For the purposes of evaluation, the device used for this study was the Phantom Omni device from Sensable Technologies[1]. This device offers three degrees of force-feedback output, high resolution, low friction control and 1KHz servo loop rate. The device can generate forces of approximately 0–3.3 Newtons. The device supports a wrist-size movement area (of approximately 160 x 120 x 70mm).

3.1.2 Test Trajectories

For the purposes of testing, several test trajectories were developed. The test trajectories consisted of sine, sawtooth and square waves in the X-Y and Y-Z half-planes each covering approximately half the device workspace. The X and the Z plane present similar control challenges, while the vertical plane is affected by gravitational forces on the device arm – moving the device upwards requires more force to overcome gravity. The waveform selection presents examples of both smooth and sharp, discontinuous trajectories, simulating a wide range of potential real world situations.

3.1.3 Conditions

One of the most important factors in an effective playback system is stability under a wide range of conditions. In order to evaluate the controller in several common situations, the trajectories were played back under varying constraints. These were:

[1] http://www.sensable.com

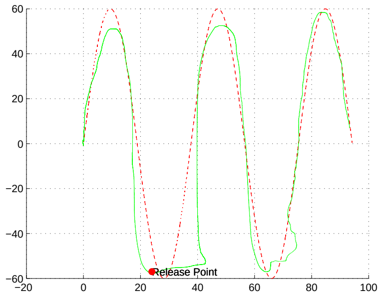

Figure 2: Device following a sine wave pattern, where the arm is held and then suddenly released (release point is marked by a circle). The controller recovers rapidly.

Wave	Held RMS Error (mm)	Unheld RMS Error (mm)
Sine XY	10.60	6.98
Square XY	8.85	6.81
Saw XY	7.46	6.47
Sine YZ	10.61	7.73
Square YZ	10.36	7.71
Saw YZ	9.36	7.30

Table 1: Root mean squared error for each of six test waveforms, in both the human held and free configurations.

- Held – the device is lightly held by a user, who is being dragged through the trajectory.
- Unheld – the device moves freely.
- Artificially Perturbed – the device moves freely, but experiences a sudden simulated disturbing force of 2 Newtons for quarter of a second during the playback.
- Object Contact – the trajectory moves through a firm virtual sphere simulation.
- Held with release – the device is held as in the first condition and is released part of the way through a trajectory.

3.1.4 Error Measurement

To evaluate the quality of playback, the root mean squared error (RMS error) is used. This gives the average error between the desired playback position and the actual device position, over the entire trajectory, in millimetres.

3.2 Results

3.3 Total Error Results

The errors for the test trajectories are summarized in Table 1. It can be seen that the error in the held case is higher due to perturbations to the device end effector from the user's arm. Error is also slightly higher in the YZ case, where the device has to continuously move against gravity. In all cases, the error was generally small, in the worst case having approximately 1cm RMS error. Figure 3 shows the overlaid plots of the actual playback position and reference trajectory for the held and unheld cases described here. It can be seen that the device remains stable, and follows with small deviations around the trajectory.

One of the critical criteria for a playblack system is the stability of its output under varying environmental conditions. Several of

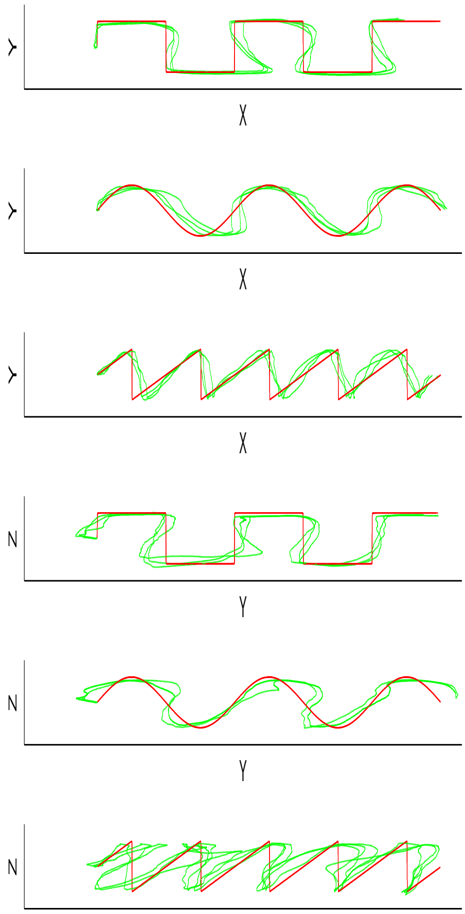

Figure 3: Reference trajectories and actual tracked trajectories for three replications of each test signal. The test signals, from top to bottom, are: Sine XY-plane, Square XY-plane, Saw XY-plane, Sine YZ-plane, Square YZ-plane, Saw YZ-plane

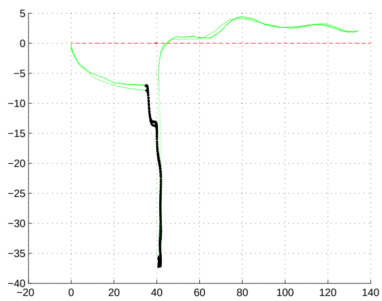

Figure 4: Position of the device (in XY) while the device follows a straight line trajectory, and is suddenly disturbed by a 2N force. The device recovers from the disturbance. The darker section indicates when the force is being applied.

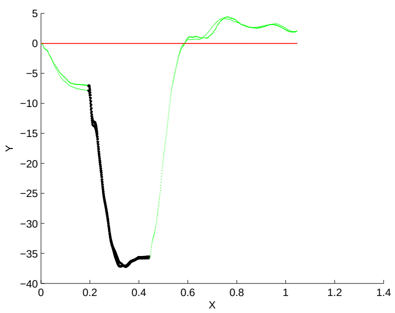

Figure 5: As in Figure 4, but time series plot of the Y value. The darker section indicates when the force is being applied.

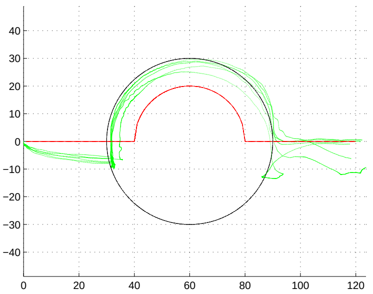

Figure 6: Trajectory of the device as it attempts to follow the smooth inner target trajectory. There is a simulated sphere object in the path of the device (outer circle), which repels the cursor.

the test cases as designed to test the efficiacy of the playback under perturbations likely to be encountered in real systems.

Figure 2 shows a sine wave plot where the device is held for the initial part of the trajectory and then released. The controller quickly retracks the target path without instability or significant deviations. This condition test the stability in a situation where the resistance on the device suddenly decreases. Figure 4 and 5 show the effect of artificially adding a sudden 2N force to the device. The controller adjusts the playback force appropriately and begins moving towards the reference trajectory after 200ms. When the disturbing force is removed, the controller remains stable.

Figure 6 shows the controller coping with contact with a simulated object; here the trajectory moves through a virtual sphere. The controller stabily tracks the trajectory through the object. In this situation, a user can feel both the playback force and the reaction force of the object.

4 Conclusions

The results demostrate that the playback remains stable under all tested conditions. This makes it widely suitable for implementation as a general playback technique, especially where users may not be familiar with the characteristics of the device. Similarly, the algorithm adapts forces from playback to cope with situations where the tension the user applies is varied rapidly (e.g. when the device is suddenly released). The algorithm copes with contact with simulated objects, making it easy to incorporate into training environments where object manipulation may be important.

The small errors in playback are due to a number of factors; gravity, device intertia and permitting the playback bead to lead the controller position, leading to slight rounding of sharp corners. The rounding can be reduced by decreasing the progression error threshold, at the cost of potentially jerky response.

4.1 Outlook

There are a number of potential extensions to this work. One useful addition would be a constraint-based playback system, where the user is constrained a tunnel around the path, but can move along the tunnel at will. There is also potential for improvements in controller design; for example including velocity control as well as position control for dynamic gesture playback.

4.2 Library

An open source library incoroporating these techniques has been developed, suitable for use with any force feedback device, with pre-tuned settings for the Sensable Omni and the Sensable Phantom 1.5. Parameters are easily adapted to other force-feedback devices. It is currently being used in a medical training simulation to allow teaching to take place even when the tutor is not present. The library, with documentation, is available for download at http://www.dcs.gla.ac.uk/∼ac/pidlib.html.

Acknowledgements

The authors would like to acknowledge the MICOLE project and the PASCAL project, both part of the European Commission Framework 6 programme, for funding this work.

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