

Exploratory Statistical Graphics for an Initial Motion Control Experiment

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Abstract

We describe the use of high dimensional data visualization tools and techniques in the study of motor control in arm motion. Visualizing the captured motion data provides immediate feedback and guidance in the design of our experiments as well as longer range benefits in uncovering relationships in the data.

Even though the experiments described here are only initial experiments of human arm motion, they provide important information for our future work that combines aspects of motion control, virtual reality, and dynamic statistical graphics.

1 Introduction

Historically, the study of biomedical phenomena has been limited by a lack of familiarity with the application of robust data analysis and visualization tools. Although quite sophisticated tools have been available for many years, their use has only flourished in domains where researchers have been made aware of their enormous value.

It is clear that more complex experimental paradigms are developed when experimenters understand the arsenal of analytical tools available to them and that preliminary visualization of experimental data can effect prudent and timely changes in the design of an experiment. This paper addresses collection and preliminary visualization of human arm motion data and the impact on experimental design. The fundamental research intends to characterize very complex Central Nervous System (CNS) control of movement and interactions between the visual and motor systems.

In Section 2 we provide a short motivation why to study motor control. In Section 3 we describe a particular motor control experiment and focus on the visualization of the collected data in Section 4. In Section 5 we

provide an outlook on future work in the fields of virtual reality and the virtual rendering of an arm. We end with a conclusion in Section 6. Extended (color) images of the figures referred to in the following sections are available on our web site <http://www.Healthrx.com/motion/Interface98.htm>.

2 Study of Motor Control

Our motion experiments are motivated by the question of how the CNS controls movements. What are the interactions between visual, proprioceptive and vestibular systems in motor control? How can we best study these interactions in order to better understand the motor system?

In general, we know that the motor system builds a model of its environment and then responds to perturbations by adaptation (Gandolfo, Mussa-Ivaldi & Bizzi 1996). The human brain builds its map based on what it sees (visual input), what its joints, ligaments and muscles report about their position (proprioceptive input), and what the inner ears tell it about the orientation of the head with respect to gravity (vestibular input). There are circumstances where humans lose some part of this system but quickly adapt.

One of the challenges in the study of motor control is to devise ways to measure adaptation after perturbation. There are many devices in the motor control research community that measure combinations of force and muscle recruitment in movement during which forces (perturbations) are introduced (Gomi & Kawato 1996).

Extensive studies on human (arm) movements have been conducted, e.g., Darling & Cooke (1987), Cooke & Brown (1986), Brown & Cooke (1990), and Cooke & Brown (1990). Unfortunately, typically only data for very short movements has been collected due to technical constraints. Statistical displays that have been used

are restricted to time series plots or scatterplots of two of the observed variables. However, much more is possible with respect to the amount of collected data and the use of current visualization techniques as we will see throughout this paper.

3 The Experiment

All our experiments described within this paper relate to a subject’s arm motion while performing a simple repetitive task. The subject, in our case a 32-year-old Caucasian male, was fitted with a set of three sensors from a device called the Flock of Birds[®] (FOB) from Ascension Technology Corporation (<http://www.ascension-tech.com/flock.htm>). The first sensor was attached to the upper arm in between the shoulder and the elbow. The second sensor was attached to the forearm in between the elbow and the wrist. The third sensor was attached to the back of the hand.

The FOB uses radio frequency (RF) to communicate each sensor’s Cartesian coordinates (X, Y, and Z), and pitch, roll, and yaw angles to a base unit. The receiver for the base unit can be placed anywhere and is the origin of the coordinate system which provides some flexibility in design. Problems with body movement can be ameliorated by recording the data relative to some fixed body point. For example, if the subject’s upper body movement causes distortion, the base unit sensor can be affixed to the shoulder so that all sensor positions are relative to a moving origin at the shoulder. The six parameters for each sensor are transmitted and read at approximately 100 Hz in the best case. As sensors are added, the bandwidth decreases due to processing overhead. With three sensors we were able to achieve a rate of approximately 60 Hz. In statistical terminology, we collect 18-dimensional data (3 FOBs \times 6 coordinates/angles) for each point in time.

Our subject performed four tasks. The first was a plain finger-to-nose neurologic test simply to validate the equipment. The equipment worked as expected. The remaining experiments measured the arm motion while tracing a circle in front of the subject in three orientations: horizontal, vertical, and at a 45-degree angle. For each orientation the subject traced a path without lifting his finger from the center of the circle to the proximal edge, then 360-degrees around the circle counterclockwise, back to the center, back to the edge, clockwise, repeating this path once (Figure 1). The origin of the coordinate system was approximately one meter opposite the subject at the same height as the target.

A small program running on the personal computer to which the base unit is attached (via a serial port) polls

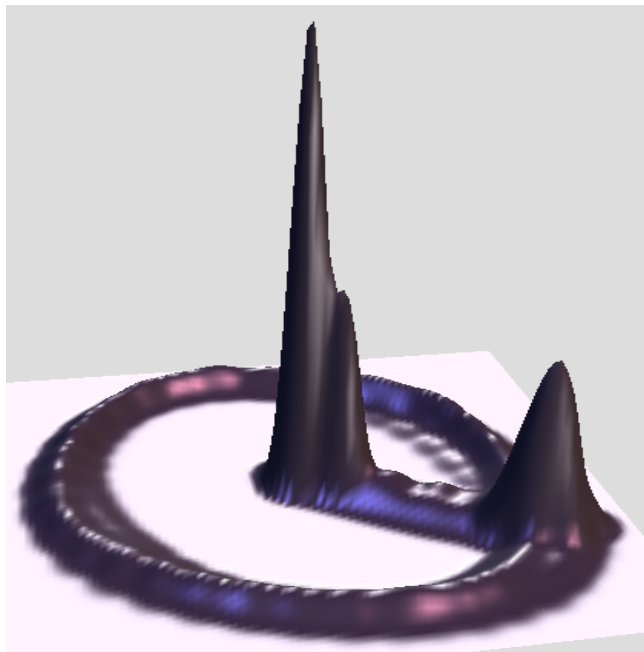


Figure 1: This bivariate density plot, produced in ExplorN, illustrates the path traced in our experiments. The plot is higher where there are more points at the particular coordinate. One can readily see that there is a pause at the center of the circle as well as a shorter pause at the edge closest to the subject. The relative evenness of the rest of the circle indicates that the movement for each individual path around the circle has been done at a consistent speed.

for data and writes the stream to a disk file. The files consist of records of the six FOB coordinates/angles plus an FOB identifier. Time is implicit in the data.

The FOB seems to be adequate for gross studies of motion but suffers from RF reflection problems typical for this sort of device. We are aware that FOB data is systematically distorted. However, solutions how to correct this data are known (Livingston & State 1997) and will be used for our future work.

4 Visualization

The purpose of visualization through exploratory interactive and dynamic statistical graphics is an important issue for our experiments. Once the subject has been detached from the sensors and other devices, it is essentially impossible to recreate the experiment. In our work we encountered many problems that could invalidate entire experiments, but might be correctable if noticed in time.

Our work began with the visualization of previously acquired data in order to simply reproduce the motion. Our first program displayed the data from three points

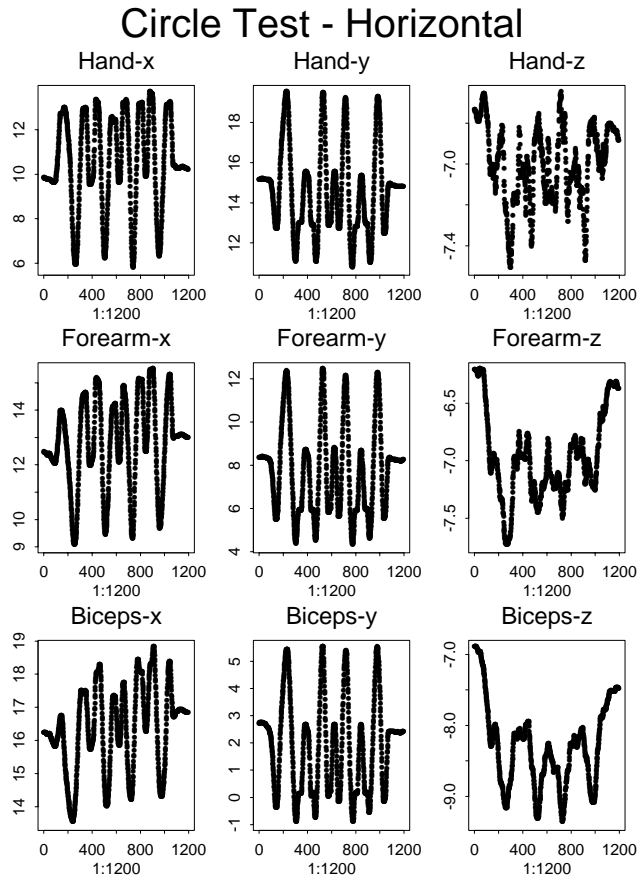


Figure 2: These plots show the X, Y, and Z coordinates (left to right) for the hand, forearm and biceps (top to bottom) for “normal” FOB data for the horizontal movement.

of view in a stick figure model of the arm. The next version implemented an OpenGL display that was a full 3D representation using spheres connected by lines. The improvement was the ability to view the motion from any angle. This program can read data files or be driven directly during data capture to provide a check of data plausibility. Versions were written for both the PC and SGI workstation.

The first of our data visualization steps from a statistical point of view was to look at time series plots of the data using S-Plus (MathSoft, Seattle, WA). Since we are conducting repeated regular movements, there should be a regular pattern in these plots. This is indeed the case, as Figure 2 shows. However, there seems to be a visible trend when looking at the plots for “Forearm-x” and “Biceps-x”. In our initial experiments, this trend most likely can be attributed to undesirable effects of the experimental setup. We assume that either the subject’s chair moved or the target itself moved during the arm movements. As a conclusion, one should make sure that everything is fixed and attached in future experiments.

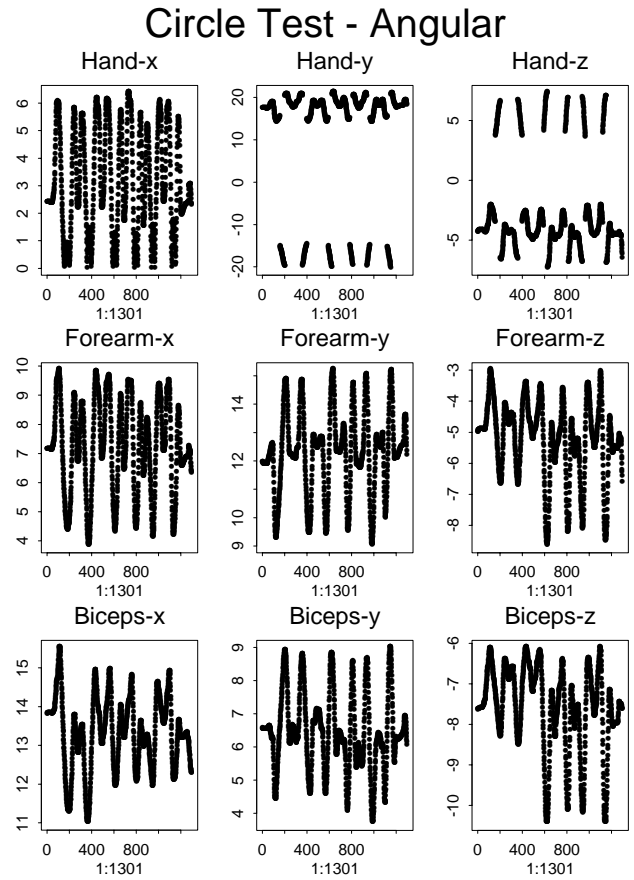


Figure 3: These plots show the X, Y, and Z coordinates (left to right) for the hand, forearm and biceps (top to bottom) for “abnormal” FOB data for the 45-degree angular movement.

Figure 3 shows one of the possible worst case scenarios for our experiments. The entire readings for the hand are invalid. This is obvious for “Hand-y” and “Hand-z”, but also for “Hand-x” where the peaks at the bottom are turned inwards. We do not know what caused these problems, but it appears as if at least sign bits have been recorded incorrectly.

A dynamic statistical graphics program such as XGobi (Swayne, Cook & Buja 1998) allows to explore the data through different types of scatterplots and to highlight features through linked brushing in multiple windows. Figure 4 shows a scatterplot of all measured values of Y coordinates versus X coordinates for all three FOBs for the horizontal movement.

Figure 5 shows two “linked” XGobi displays. If we “brush” (i.e., mark points with a different color and symbol) in one such linked display, points in all other linked displays will also be marked with the same color and symbol. Here we brush all points in a jittered dotplot of observation number in the left XGobi that relate to the counterclockwise movements with a solid symbol. The

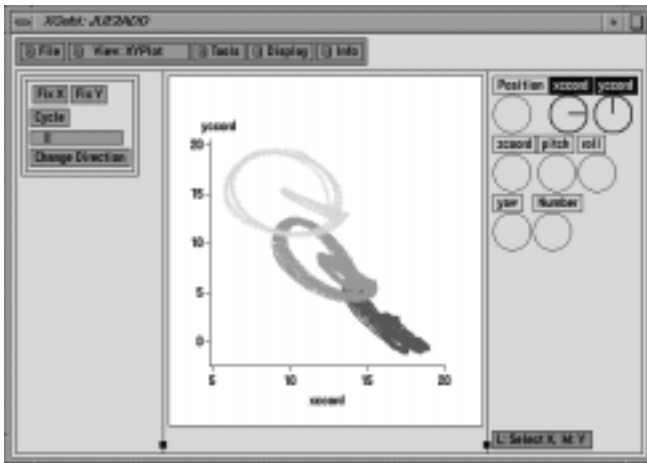


Figure 4: The XGobi window shows the main XGobi controls and a scatterplot of all measured values of Y coordinates versus X coordinates for all three FOBs for the horizontal movement. The lightest color represents the sensor attached to the hand, the middle color the forearm, and the darkest color the upper arm.

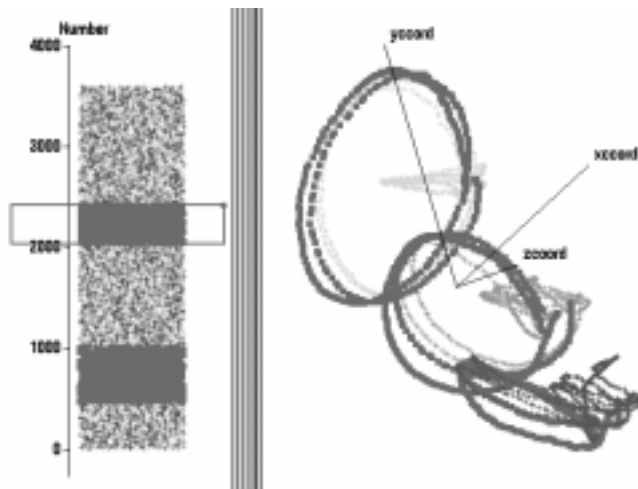


Figure 5: This figure shows two “linked” XGobi displays where the two counterclockwise movements have been brushed with a solid symbol. They clearly differ in location from the unbrushed clockwise movements.

right XGobi shows a slightly rotated 3D plot of the X, Y, and Z coordinates. Even though the visible distances in the coordinate space between the clockwise and counterclockwise movements are minor, it is reasonable to assume there are in fact differences. Assuming the subject did not make any systematic errors while performing the task, one can conclude that hand, forearm, and biceps were held slightly differently for clockwise and counterclockwise circles.

A bivariate density plot (Figure 1) of the “Hand-y”

versus “Hand-x” coordinates of the horizontal movement, produced in ExplorN (Carr, Wegman & Luo 1997), provides additional insight into the amount of time spent at a particular position. There are two peaks in the middle. These can be contributed to an intermediate stop before reverting the movement. Noticeably, the subject did not always stop at the same center point.

The bump on the edge can be contributed to a stop and change of direction from in/out-bound to circular movement and vice versa. The subject did not use a “shortcut” on its finger’s way to or from the center. Finally, the even density on the circle can be interpreted as constant speed on each of the 4 circular movements (but this may not necessarily be the same speed on each individual movement — in fact, the different thickness of the two brushed regions in the left XGobi display in Figure 5 proves that the two counterclockwise movements have been done at different speeds). Surprisingly, only very little signs of speedup/slowdown can be found towards the bump on the edge. It appears as if the subject stopped very quickly and precisely at one point.

The software packages XGobi and ExplorN used for visualization within this section can be downloaded for free from <http://www.research.att.com/~andreas/xgobi/index.html> and <ftp://www.galaxy.gmu.edu/pub/software/>, respectively.

5 Future Work

5.1 Virtual Reality

The experiments described so far were performed in “reality” where we are measuring our subject’s arm motion with no perturbations. Our next goal is to gain insight into how the brain adapts to changes in the environment.

Since there is a clear mapping between visual and proprioceptive systems, it is a natural extension of these experiments to focus on perturbations in the visual system, which is a perfect application of virtual reality (VR) techniques. Using VR we can design experiments for tasks as natural as tracking a virtual object or artificial as displaying the subject’s movement in such a way that the normal relations between movement and vision no longer hold. The general design will produce a target in 3-space for which the eccentricity or the path, its orientation and absolute size can be varied. The target can thus range from a straight line to a circle. The subject will be required to trace out the target with the tip of his/her virtual finger. Initially the feedback of the finger position will be provided by the FOB and displayed to the subject as a simple object such as a small sphere. By moving the arm the subject is able to move the sphere

along the virtual path.

Two kinds of target movement will be available. In the first, the target appears as a ring or torus. The subject’s task is to move his/her finger around the ring in one direction or the other at his/her own speed. By changing the eccentricity and orientation of the ellipse, questions about speed choices and joint movement related to curvature and spatial orientation can be approached.

In the second type of target movement the target is a sphere which moves along an elliptical path. The subject’s task is to keep his/her finger (represented by the feedback sphere) on the target sphere. This is the type of visual feedback called “pursuit tracking”. Rather than following along a path whose properties are known a priori, the subject is pursuing his/her target. In this kind of experiment the path of the target can be preprogrammed or change in response to the subject’s motion. This is particularly interesting where we can measure eye movement. It is known that there are two types of eye movement, saccadic and smooth pursuit. In making periodic movements (e.g. pursuing a target moving sinusoidally in one dimension) the brain switches from one type of eye movement to another above a certain frequency of target movement.

It is possible to capture a subject’s eye position in the X–Y plane using special infrared source and detector pairs affixed to special glasses. Magnetic coil devices that measure gaze into 3D space are still only used in research animals as they must be affixed to the cornea.

In both types of target movement we have the ability to capture all of the data — from arm motion and eye movement, to all of the target parameters. This makes for rich fodder for high dimensional analytical tools. Possible developments in this work can be used to test neuromotor control skills in subjects with specific pharmacological or psycho–pathological conditions such as alcohol or drug influence and sleep deprivation.

5.2 Virtual Arm

An obvious extension of the VR setting is to create a more realistic arm for the subject to see in his/her virtual world. We will have the data available in fairly high resolution to pass to animation tools.

Typically, motion capture (mocap) data for animation is collected in the form of explicit X, Y, and Z coordinates. The methods used in animation involve using this data to pull the geometry into position.

The challenge of animating an arm in a realistic manner involves accurate recreation of:

- Extension, flexion, adduction, abduction, prona-

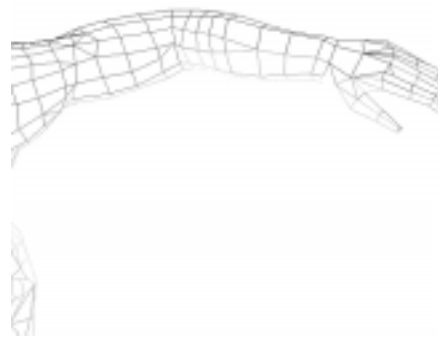


Figure 6: Simple arm rendering can be made from scanning the arm with the Flock of Birds.

tion, and supination of the shoulder

- Extension and flexion of the elbow
- Pronation and supination of the forearm
- Flexion and extension of the wrist.

A variety of schemata can be used to convert incoming mocap sensor data to movement of a geometrical model (Figure 6). A number of high–end and mid–range 3D animation software packages such as Softimage 3D (<http://www.softimage.com/>) and Alias PowerAnimator (<http://www.aw.sgi.com/pages/home/index.html>) can accept mocap data. It should be noted that these packages will frequently use different terminology to describe similar functions or methods. Here we use terms specific to Softimage 3D.

A direct method of implementing XYZ data is to create a two joint skeletal chain. Each portion of the chain corresponds roughly to a part of the human arm:

Chain	Arm Counterpart
Root	Shoulder Joint
First Joint	Upper Arm
Second Joint	Forearm
Effector	Wrist

Where the two joints meet is equivalent to the elbow joint. An additional single joint chain would also be attached to the end of the second joint (effector) in a subordinate relationship. This additional chain would mimic the gross movements of the hand. Additional skeletal chains can be built to accommodate naturalistic digit function.

Data from sensors placed at the wrist and on the back of the hand will correspond to the arm effector and hand effector respectively. In this manner, extension and flexion of the shoulder, elbow and wrist joints are accomplished. As a single joint chain can move in two axes, the

hand sensor data can also provide for lateral movement. A sensor placed on the elbow will supply point-data to produce abduction and adduction of the shoulder joint.

When supplied in the proper format, the incoming data stream can be converted by utility software into function curves that show position in XYZ space over time. The animator then assigns the function curves to the appropriate part of the model. Through several iterations of tests and refinements, the mocap data should cause the model arm to move as desired.

6 Conclusions

While the essence of this work is to view our arm motion data as high dimensional data using appropriate tools, we must be very careful in interpreting the data from these initial experiments. Beyond the data captured from the FOB sensors, there are derived measures we should be looking at. The plotted data were the mid-hand, mid-forearm and mid-upper arm positions in Cartesian space. Physiologically and theoretically, there would be great interest in looking at the actual joint angles and their temporal and spatial interactions. Indeed, adding these into the mix of the Cartesian positions of the limb segments would be a valuable expansion of our analytic repertoire.

In the time series plots, one must be careful with interpretations of apparently strongly correlated variables. Since this is a fixed link, three segment system, movement of a proximal segment in any one dimension will of necessity produce highly correlated movements of each distal segment in the same dimension. For example, we would expect upper arm and forearm movement in the vertical axis to be highly correlated just because of the mechanical linkage of the system. Thus, in order to get meaning from the interrelations between variables we need to have a model which will predict on purely mechanical grounds what effects movement of one segment will have on movement of the other segments. We then need to be able to subtract these mechanical linkage effects from the actual data. What is left should then be motion which is actively brought about by the nervous system.

There are many useful visualization tools available to us. They range from simple time series plots, 3D renderings, and density plots to scatterplots connected through linked brushing. All have proven useful for immediate visualization during the experiment as well as for an exploratory visual analysis after the experiment.

While in these initial experiments problems with the recorded data were immediately visible, our ongoing research will result in more complicated movements that

require immediate graphical verification. Think of an experiment where the subject must follow a moving object in a virtual reality environment. Assume the object makes frequent changes in direction. In such a case, could it not be possible that the wrong direction of the peaks observed in Figure 3 for “Hand-x” would be incorrectly attributed to a change in direction and not to the recording error that actually occurred? The more time that elapses between conducting the experiments and visualizing/analyzing the data, the more difficult it will be to resolve inconsistencies and answer questions about the data.

In summary, this paper has shown that: (i) immediate visualization is highly recommended for our kind of motion control experiments and (ii) visualization is a very effective exploratory tool for motion control data.

Acknowledgments

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