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A Natural and Effective Calibration of the CyberGlove

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Abstract

This work addresses the calibration of the CyberGlove, a device which provides information about the position and attitude in space of all the components of the user hand in a haptic system for the fruition of digital 3D contents by blind people. A realistic haptic interaction requires a reliable detection of user movements and a good calibration of the device to account for size and articulation capability of the specific hand. At the same time the application of interest calls for a calibration procedure that should be executable in a natural and straightforward way by every user. The two methods provided by the CyberGlove software are not suitable for these purposes: one is very simple and fast but produces quite imprecise results while the other is effective and accurate but involves a complex and cumbersome trial-and-error process not suited for general users. The proposed method aims to reach satisfactory results using a intuitive and simple approach. The user is asked to assume with his hand several pre-defined poses, each supplying the sensors output associated to known joints' angles. Combining these data with the constraints derived by the anatomical structure of the hand it is possible to evaluate the values of the two parameters, gain and offset, that drive the digitalization of the sensor output. This process, in spite of its simplicity, has provided satisfactory results in several experimental sessions, enabling a realistic and reliable mirroring of user movements in the virtual space.

"Categories and Subject Descriptors (according to ACM CCS):" H.1.2 [Models and Principles]: Human Factors H.5.2 [Information Interfaces and Presentation]: Haptic I/O I.3.4 [Computer Graphics]: Virtual Device Interfaces

1. Introduction

This work describes a part of a project whose goal is the development of a system based on haptic interfaces for the exploration of virtual 3D models by blind people [DRAD05]. The word haptic comes from the Greek word *haptesthai* (to touch) and is used to qualify devices and systems related to or based on the sense of touch. A haptic interface is a device from which the user can receive tactile or kinaesthetic sensations. This hardware is useful for applications in which the sense of vision can be fruitfully complemented by touch to achieve a simple, complete and immediate interaction with a virtual environment. Using suitable devices and properly designed software a bi-directional information and energy exchange can be established between the user and the virtual space. Tracker devices provide to the system the information necessary to update position and attitude of the avatar representing the user in the virtual space. The system simulates the physical interaction between the avatar and the virtual scene from which it derives forces that are sent back as mechanical energy perceptible by the user as passive resistance.

Haptic devices are used in games, advanced robotics (as surgical and spatial robotics), fruition of virtual reality, tale manipulation, simulated training, exploration of three dimensional virtual museum, … An interesting application is the development of innovative interfaces for blind people. Haptic interaction with virtual models is expected to provide two advantages in this context. First of all, it can allow the exploration of objects that for dimension, location or delicacy could not be physically touched (statues, architectural or archaeological sites, etc.) as long as the experience of concepts (in mathematics, biology, chemistry, geography, ...) for which suitable physical artefacts would be necessary and not always completely satisfactory. Haptic interface can bring a further value by enhancing the understanding of the real world. In fact, the touch is a serial, single scale sense: only a point at a time can be perceived and the level of details that can be experienced depends on the relative size between the objects and the fingertips, both unchangeable. To collect and to organize this huge amount of sensations into a meaningful mental schema is a challenging task. Haptic interfaces, complemented by suitably written software and properly designed models, can offer a multi-resolution experience of virtual objects that can mimic some properties of vision: objects can be perceived at several level of details, each with a different amount and kind of details. The blind can quickly acquire from the rough level a general idea of the object on which the following explorations can add new elements. At each level the relative size of fingertips with respect to the objects can be modulated to enhance the perception. Finally, the analysis of exploration paths followed by users and of their efficiency can allow the automatic definition of optimal paths around the objects: the system can guide the following users, even by applying constraining forces to their movements, across the most meaningful and useful portions of the scene.

The system uses the CyberForce device, from Immersion Corporation Inc., equipped with the CyberGrasp and the CyberGlove [IMM]. The main modules of the system architecture, depicted in Figure 1, are:

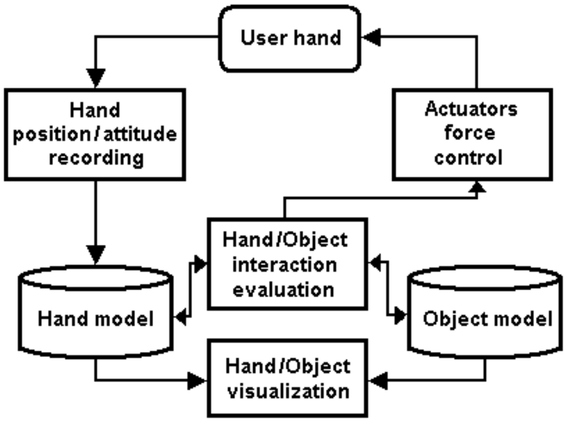


Figure 1: *The architecture of the haptic system.*

Hand position/attitude recording, which continuously updates the user hand virtual model depending on the data received by the Cyberforce acting as a 3D tracker.

Hand/object interaction evaluation, which defines if collisions occur between the virtual hand and the objects and simulates the physical forces.

Actuators force control, which adapts the calculated ideal forces to the mechanical capabilities of the physical device.

To concentrate on the study of a model allowing a realistic interaction between a virtual hand and the virtual scene the system is being temporarily used to simulate a single fingertip using a proper probe connected to the CyberForce (Figure 2). Several experimental evidences point out the use of all the five fingers (and hopefully of both the hands) as a way to reach a more natural and effective exploration especially for complex scenes. Human hand is a very rich channel of interaction between humans and the environment. A good comprehension of the features of the human hand from an anatomic and sensorial point of view is important for its realistic simulation in a virtual environment. The contact with objects normally provides to skin receptors tactile information about the spatial distribution, the pressure, the temperature and the object texture. At the same time joints, tendons and arms muscles supply kinaesthetic information about object position, velocity, acceleration and contact forces. The generation of these perceptions requires the position and articulation of the whole hand to be precisely known. This can be done using appearance-based and model-based methods. The formers map images of the real hand to its virtual counterpart. The latter update a deformable model of the hand, moving in a virtual space, on the basis of the movement of the real hand, detected from images acquired from the real world or provided by sensors distributed on suitable gloves worn by the user. The position (attitude) of the wrist in the space is provided by tracker devices with three (six) degrees of freedom (DOF). Our system uses the CyberGlove to track the articulation of the user's hand and the CyberForce to identify position and attitude of the wrist [DNR*04].

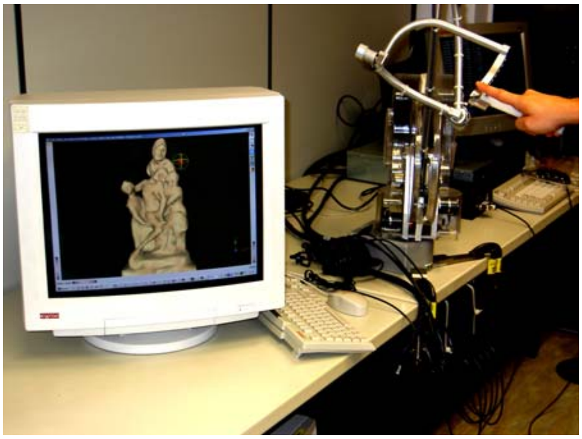


Figure 2: *A picture of the system. The screen shows the virtual space in which the avatar, representing the fingertip of the user hand on the right, interacts with a sculpture.*

The CyberGlove sends to the system data about all the components of the human hand acquired by suitable sensors inserted in a glove. To account for the light differences between users (size of the hand, range of movements for each part of the fingers, …) it needs to be calibrated. The result of the calibration is a proper value for two parameters, gain and offset, that control the digitalization of the signal provided by the different sensors. On the basis of these parameters the rough data provided by the glove can be translated in angles, measured in radians. The calibration operation needs to be fast and simple to allow a large number of people, often without specific knowledge about 3D tracking and haptic interfaces, to use the system. The simple calibration tool provided with the CyberGlove is easy but does not reach a satisfactory precision. On the other side, the manual setting of gain and offset for each sensor can reach very good results but is a cumbersome and complex trial-and-error process, definitely too difficult for a normal user. For these reasons a new calibration routine has been proposed that wants to be more comfortable, easy and effective with respect to the native one. With this new calibration the gain and offset values for each sensor are set starting from the rough data generated by the CyberGlove while the user assumes some fundamental poses. These poses determine the minimum and maximum angles for each hand movement; in this way a linear interpolation has been made to track the entire movement. Furthermore a filter has been added to overcome the noise affecting the rough data coming from the CyberGlove.

The paper is organized as follows: in section two the CyberGlove with the automatic and manual calibration method is described. Then the constraints among the fingers joints and the proposed glove calibration method are presented. Finally some results are reported.

2. The CyberGlove

The input device used to capture data about the user hand is the CyberGlove [IMM02] (produced by Immersion Corporation), which is equipped with 22 sensors (flexion and abduction Figure 3) that measure the changes of resistance arising when they are bent to map movements of hand and fingers onto digital data. Using these data it is possible to keep a virtual hand (avatar) in the virtual space constantly updated with any movement of its real counterpart.

The CyberGlove Interface Unit (CGIU) converts the output voltage of each sensor into an integer number in the range $[0-255]$ using an 8 bit analog-to-digital converter (ADC). The digitalisation process uses the two parameters offset and gain, set in hardware at the factory, to keep the digital values into the smaller range $[40-220]$. This prevents the system from going out of the limits of the ADC for users that can bend or extend the sensors beyond the capabilities of the average hand.

The digital values are converted in angles, expressed in radians, according to the following linear equation:

Angle = Gain * (Raw_Output - Offset) (1)

where this gain and offset are software parameters obtained by calibrating the CyberGlove to match the characteristic of each specific user. The linear relation between the output voltage of each sensor and the change in bend angle does not cause any loss of resolution at joint extremes.

A correct calibration procedure is necessary to evaluate flexion and abduction values of the hand joints, starting from the raw data provided by the device. In fact, the CyberGlove provides a very rough estimate of hand movements when used with default values for gain and offset due to anatomical differences between users.

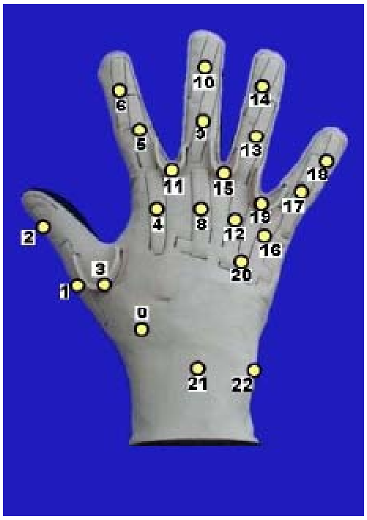


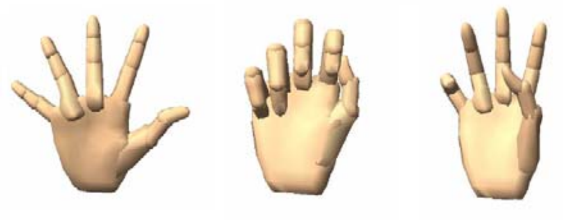
Figure 3: *The CyberGlove with its 22 sensors.*

The calibration routine, included in the glove management software, allows the user to calibrate the glove making two different movements (Figure 4). The first one consists in flattening the hand as if it is pressed against a flat surface; the latest consists in making an OK sign by touching the tips of the index finger and thumb together. The described positions assumed by the hand during the calibration step do not affect thumb, abduction and wrist sensors. The obtained results have been experimentally found not satisfactory.

Figure 4: *The positions of the hand used by the calibration software provided with the CyberGlove software.*

Figure 5 reports the rendering after this calibration: in (a) the user keeps his hand flat with the maximum abduction; in (b) the fingers are clinched as a fist; n (c) the tips of little finger and thumb are touching. It is evident that movements of the physical hand are not faithfully reported on the virtual hand.

To obtain a more reliable calibration, the CyberGlove software offers an advanced procedure that consists in setting by hand gain and offset for each sensor. Changes in the offset parameter affects the position of the starting point for each joint's range while the gain determines the extension of movements allowed for that joint. The process strongly increases the quality of rendering but it is a cumbersome, long and complex trial-and-error process that is not natural and intuitive for the general users.



(a) (b) (c)

Figure 5: *The effect of the calibration included in the CyberGlove software. The rendering in (a) corresponds to a user keeping his hand flat with the maximum abduction. In (b) the fingers should be clinched as a fist; in (c) the tips of little finger and thumb should touch.*

3. The proposed automatic calibration

Aim of this work is to define a new calibration routine that overcomes the drawbacks of the two native calibration methods provided by the CyberGlove. The main goal is to achieve a precision close to the one attainable by the manual setting of the different parameters but using the simple and intuitive approach of processing a proper set of positions of the users' hand. The data acquired in these pre-defined positions, combined with a suitable set of anatomical constraints [LWH00][LK95], allow the calibration to be done in a quite natural and effective way.

3.1. The model of the human hand

The human hand can be defined as a complex mechanical structure with about thirty degrees of freedom (DOF). This structure includes bones, muscles and tendons connecting them. Each joint movement defines a rotation around an axis and can be expressed by the following notation:

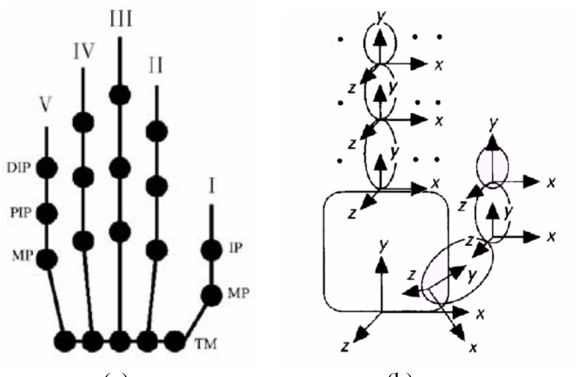
$$\theta^{\alpha}_{\beta(\gamma)}$$

where θ is the rotation angle of the joint β around the rotation axis α ; the joint β belongs to finger γ .

The hand joints considered to construct a virtual hand model are pointed out in Figure 6a, where:

DIP = Distal Inter-Phalangeal joint
PIP = Proximal Inter-Phalanageal joint
MP = Metacarpo-Phalangeal joint
IP = Inter-Phalangeal joint
TM = Trapezio Metacarpal joint

The joints movements are reported in Figure 6b with respect to a reference frame.



(a) (b)

Figure 6: *On the left, a schema of the human hand with the labels used to indicate fingers and joints. On the right the reference frames for the different joints are reported.*

Each finger has four DOFs. In fact index, middle, ring and little fingers can be flexed at DIP, PIP and MP joints and adducted/abducted at MP joint. Moreover the thumb has flexion and abduction/adduction at MP joint, rotation at TM joint and flexion at IP joint. In this way a twenty DOFs hand model is accomplished; six DOFs for rotation and translation of the overall hand in the space must be added, obtaining a twenty six DOFs model.

To opportunely model a human hand and create a reliable virtual representation of its movements the analysis of its anatomical constraints is essential. A set of constraints must be defined to avoid unfeasible hand configurations. Three different types of constraints can be devised.

The first type represents the movements limits due to hand anatomy and identifies the range of motion for each finger in absence of external forces, whose static constraints are expressed by the following inequalities:

1) $0^o \le \theta^X_{DIP(j)} \le 90^o$

2) $0^o \le \theta^X_{PIP(j)} \le 110^o$

3) $0^o \le \theta^X_{MP(j)} \le 90^o$

4) $-15^o \le \theta^Z_{MP(y,y+1)} \le 15^o$

where j = { II, III, IV, V } and y = { II, III, IV }.

Thumb is associated to more complex constraints due to its link with the palm and to its capability to oppose to the other fingers. These constraints, defined in an empirical way [RG91], after some tests have been formalized by:

5) $-45^o \le \theta^X_{IP} \le 90^o$

6) $0^o \le \theta^X_{MP(I)} \le 45^o$

7) $0^o \le \theta^Z_{MP(I,II)} \le 90^o$

8) $0^o \le \theta^Y_{TM} \le 30^o$

The second type of constraints represents the dynamical limits imposed on joints by their simultaneous movements. They can be divided in intra-finger (between joints of the same finger) and inter-finger (between joints of different fingers) constraints. The main intra-finger constraint states that the bents of DIP and PIP joints are correlated and applies to index, middle, ring and little fingers. This relation can be defined as follows:

9) $$\theta_{DIP} = \frac{2}{3}\theta_{PIP}$$

Another intra-finger constraint bounds the flexion of the MP joints depending on its abduction/adduction. It states that an increment of the MP joint angle corresponds a decrement of the abduction/adduction angle of the same joint; this happens, for example, when the fist is clenched and is described by the following inequality:

10) $$0^o \le \theta^Z_{MP(i,y)} \le +K * 15^o$$

where $K = 1 - \frac{\theta^X_{MP(i)}}{90^0}$ and i, y = { II, III, IV, V }.

The main inter-finger constraint relates the flexion or the extension of a finger to the flexion or the extension of the adjacent fingers and applies to MP joints. This relationship is expressed by the following inequalities:

11)
$$\max((\theta^X_{MP(III)} - 54^o), 0^o) \le \theta^X_{MP(II)} \le$$
$$\min((\theta^X_{MP(III)} + 25), 90^o)$$

12)
$$\max((\theta^X_{MP(II)} - 25^o), (\theta^X_{MP(IV)} - 45^o), 0^o) \le \theta^X_{MP(III)} \le$$
$$\min((\theta^X_{MP(II)} + 54), (\theta^X_{MP(IV)} + 20), 90^o)$$

13)
$$\max((\theta^X_{MP(III)} - 20^o), (\theta^X_{MP(V)} - 44^o), 0^o) \le \theta^X_{MP(IV)} \le$$
$$\min((\theta^X_{MP(III)} + 45^o), (\theta^X_{MP(III)} + 48^o), 90^o)$$

14)
$$\max((\theta^X_{MP(IV)} - 48), 0^o) \le \theta^X_{MP(V)} \le$$
$$\min((\theta^X_{MP(IV)} + 44^o), 90^o)$$

In these inequalities, the values 0^o and 90^o correspond to the minimum and maximum angles defined by the static constraint n. 3; in this way the dynamic constraints defined on adjacent fingers do not clash with the static ones. A third type of constraints, related to the naturalness of hand motion, is more subtle to be detected and explicitly defined in terms of equalities or inequalities and will not be considered in this work.

3.2. The proposed approach to calibration

In a previous work the linear behaviour of the CyberGlove sensors has been proved by means of statistical analysis. Moreover it has been proved that different sizes of the human hand are irrelevant for a correct calibration of the glove done on the basis of some fundamental poses of the hand. These poses define the upper and lower bounds for each feasible movement [KHW95].

Starting from these considerations the idea underlying the new calibration consists in collecting data from a number of fundamental poses each one providing useful information about a wide number of glove sensors.

The seven fundamental poses chosen for the calibration step are reported in Fig.7. The poses (a1) and (b1) allow to collect data about flexion of DIP PIP and MP of index, middle, ring and little fingers. The poses (a1) and (d1) return data about index-middle, middle-ring, ring-little fingers abduction sensors. Poses (a1) and (f1) define the thumb-index abduction. Poses (c1) and (d1) allow to collect data about thumb IP and MP. Poses (d1) and (e1) return data related to thumb rotation. Finally from poses (b1) and (g1) data for the palm bending are captured. All these pairs of poses do not collect information about the two wrist sensors but this is not a problem for our application because wrist movements are measured by the CyberForce used as a 3D tracker.

Once all the rough data have been collected from each fundamental pose, gain and offset values for the twenty sensors of interest can be evaluated by simply solving the linear equations systems:

Angle1 = Gain * (Raw_Output1 - Offset)
Angle2 = Gain * (Raw_Output2 - Offset)

where Raw_Output are the rough data for a given sensor, and Angle are the limit angles for a joint, controlled by this particular sensor, derived by the constraints. In this way the glove calibration parameters for each particular user can be evaluated: they are stored in a .ini file for successive use.

The computed gain and offset values are used at run time to update the virtual model of the hand in the virtual environment. To avoid unfeasible configurations of the virtual hand, the angle associated to each joint, computed by the equation (1), is imposed to remain in the range define by the related constraint. This also avoids the interpenetration of virtual fingers.

Fig. 7 reports some of the results obtained applying the proposed calibration routine of the glove. In particular, the images show the results obtained when the user assumes again the positions involved in the calibration step. The figure h shows each pose with its virtual counterpart.

A comparison between the results of the two calibration methods is reported in Fig. 8. The hand rendering obtained after the proposed calibration fits better the real poses of the human hand: in the first case the new calibration method allows the ring finger and thumb tips to touch each other while in the second one it avoids the index to penetrate the object.

Figure 7: *Photographs report the seven poses assumed by the user hand during the glove calibration step. The images represent the rendering of the virtual hand.*

3.3. Noise filtering

Experiments have shown that slight vibrations can be generated when the user hand stands still (even on a flat surface) by the noise in the rough data coming from the CyberGlove. In fact small variations, in the range of ±2 units from the expected rough value, have been detected (Fig. 9). This noise, caused by high sensitivity of the glove to very small movements produced by skin elasticity, can produce annoying instability in the attitude of the hand virtual model. From a haptic point of view, these instabilities can generate unrealistic sensations especially when the avatars are very close to the object surface. This drawback can be satisfactorily solved by a filter, added at run time, which ignores data variation within the range [actual rough data-1, actual rough data +1]. This method removes almost all the vibrations without introducing significant delays in the reactivity of the haptic system.

4. Conclusions

This work describes a new calibration routine for the CyberGlove to overcome some drawbacks of the native calibration software. This activity is part of a project whose goal is the development of a system based on haptic interfaces for the exploration of virtual 3D models by blind people. This new approach to calibration starts from considering the anatomy of the human hand to define some

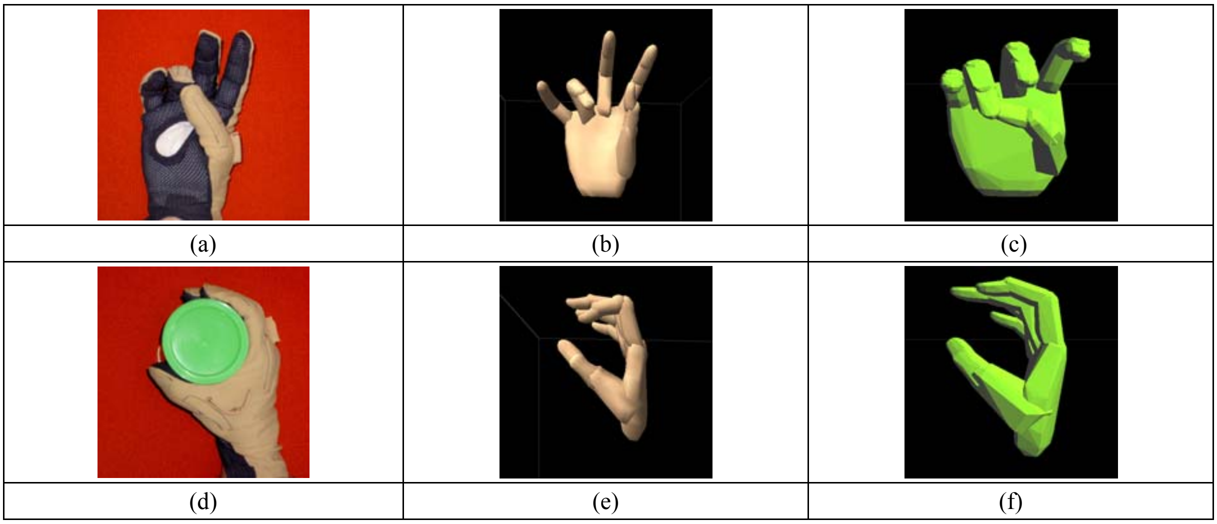


Figure 8: *The graphic rendering provided by the original calibration method (b,e) and by the proposed one (c,f) when the user assumes the hand poses shown in (a,d).*

physical constraints between its joints. This information is used and combined with the data acquired during the calibration phase to determine the parameters, gain and offset, that guide the digitalization of the output of each sensor. The method exploits also the linear behaviour of the glove sensors and the independence of the constraints on hand movements from its size.

The obtained results are reliable and significantly enhance the visual rendering of the virtual hand model that behaves in a very realistic way. A set of seven specific hand poses provides the sensor data for the upper and lower bounds of each joint. This knowledge is combined to the anatomical constraints to determine the correct setting of the free parameters. The proposed approach exhibits almost the same simplicity of the more intuitive native calibration available in the CyberGlove software but provides precision that is reasonably close to the results obtained by manual setting the free parameters, a complex and cumbersome trial-and-error process. Furthermore a simple, fast and effective filtering process is used to remove most of the noise present in the output of sensors without introducing annoying delays in the system response. The results obtained by this new calibration method are satisfactory: the system can be adapted in a simple and fast way to the specific characteristics of new users and achieve the precision required for a realistic haptic simulation.

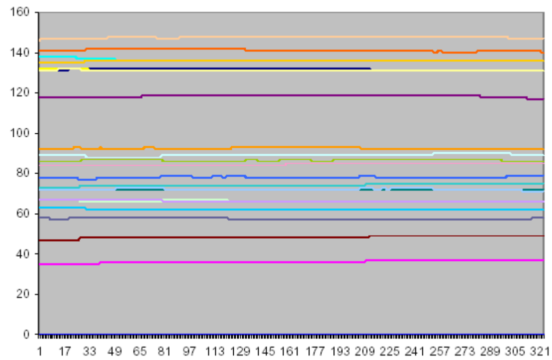


Figure 9: *Output data sampled from the CyberGlove when the hand stands still on a flat surface.*

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