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The YoYo:
A Handheld Device Combining Elastic and Isotonic Input

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Abstract: We present a new input device for controlling three-dimensional graphics applications: the YoYo. The device consists of three elastically connected rings in a row, which can be moved relative to each other. The center ring holds a tracking sensor and a few application programmable buttons. The left and the right ring are elastic six degree of freedom controllers. The device is designed for two-handed interaction and combines elastic force input and isotonic input in a single device. Compact size, symmetric shape, and the elastic properties result in a "soft" and responsive feel of the device.
We have used the YoYo for navigation and manipulation in three-dimensional graphics applications in the area of data exploration and scientific visualization. An informal user study and user observations have shown that novice users are quite confident with the device after a short introduction, and that most users alternate between using elastic rate control and isotonic control for navigation.
Keywords: User interface hardware, input devices, interaction techniques, two-handed interaction, virtual environments

1 Introduction

Navigation and spatial manipulation in three-dimensional virtual environments is often a difficult task. One of the reasons is the lack of appropriate portable and handheld input devices. A single six-degree of freedom input device allows only navigation or manipulation. Modal switching between both may interrupt the task flow. To avoid this problem, one could use either two independent input devices and assign navigation and manipulation to each device or one constructs multi-degree of freedom devices, which allow simultaneous navigation and manipulation.

We have developed the YoYo, a compact handheld interface device, which consists of three elastically connected rings arranged in a row. Our current prototype is build using two ErgoCommander® controllers attached to a center ring, which contains a tracking sensor and holds a few buttons. ErgoCommander® controllers contain elastic six degree of freedom force and torque sensors, which are used in commercial SpaceMouse™ products. The device is generally manipulated with two hands, much like a console game pad. Each elastic sensor can be manipulated independently or both sensors can be manipulated at the same time (Figure 1). The orien-

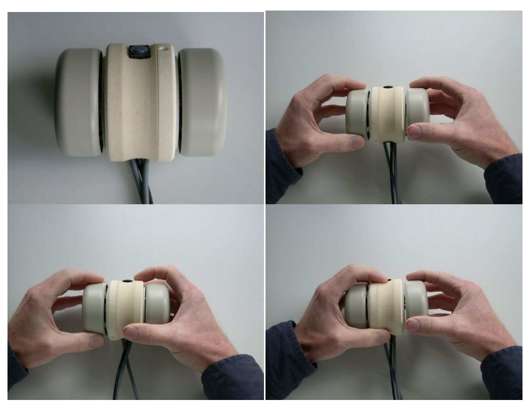

Figure 1: The Yoyo consists of three rings, which can be moved relative to each other.

tation measured by the tracking sensor allows the transformation of the inputs to the elastic controllers to a fixed world or application coordinate system. For example, if a car is positioned on the screen and the device is turned and held horizontally, pushing the left sensor would move the car to the right, if the device is held vertically, the same input would move the car down (or up).

The YoYo was originally developed for interaction in virtual environments and large screen projection systems. In these environments, input devices have to be handheld and portable, since users are typically moving around while performing interaction and navigation tasks. The development was motivated by limitations of the Cubic Mouse (Fröhlich et al, 2000a, 2000b), an isotonic input device. The Cubic Mouse is mostly used with position control techniques with limited range and fixed resolution. The YoYo combines elastic sensors with a tracking sensor, which we have used to implement combined rate- and position-control techniques for navigation and manipulation.

In our tube demo, we use the device as a prop for a simulated tube. The input forces applied to the device are used as input for a real-time finite element simulation of the tube. Twisting and bending of the YoYo results in twisting and bending of the virtual tube. This scenario allows users to easily understand how the device works.

In our data visualization scenario, the left sensor controls the position and orientation of an oil and gas data set, the right sensor controls the position and orientation of probes in the data set such as volume rendering lenses and cutting planes. We observed that our users rarely used both sensors simultaneously, so we decided to map simultaneous pushing and pulling of both sensors to increasing and decreasing of the model's size. The device allows therefore implicit transitions between scaling, navigation, and manipulation by just changing the grip on the device.

Our main contribution is the development of the first handheld interface device, which combines elastic force input and isotonic input in a single compact unit. It enables simultaneous control of a large number of degrees of freedom and allows comfortable manipulation of graphical positioning, orientation, and scaling tasks. We have built two versions of the device and integrated them with our application prototypes. The most interesting finding from an informal user study and our user observations is that most users alternate between using elastic rate control and isotonic control for navigation. It was also often remarked that quasi simultaneous navigation and manipulation are helpful and that they enjoyed using the device.

2 Related Work

In most of our application scenarios, the YoYo is used to position and orient a virtual model and manipulate a probe – such as a cutting plane – relative to the model. From this perspective, the closest relative is the head prop in (Hinckley et al, 1994a) for neurosurgical visualization. In their system, users hold a small rubber sphere or a doll's head with an embedded tracker in one hand. This head prop is used to control the orientation of a head model on the screen. The other hand holds a second prop which, for example, is used to position a cutting plane relative to the head prop. This is in contrast to our system, where both hands manipulate a single device.

The Cubic Mouse (Fröhlich et al, 2000a, 2000b) is a handheld interface device, which consists of a cube-shaped box with three orthogonal rods passing through it. The rods can be pushed, pulled, and twisted and the device contains a six-degree of freedom tracking sensor. The device is basically a handheld three-dimensional coordinate system, for which the rods the X, Y, and Z axis represent. The device is mostly used for data visualization applications, where the box represents a three-dimensional model and the rods manipulate data probes – such as cutting planes. The device is mainly used with position-control techniques, whereas the YoYo is mostly used with rate-control techniques.

There are a variety of systems using two-handed interaction techniques based on hand-held widgets, e.g. in (Mine et al, 1997) users hold a virtual widget in one hand and operate it with the other. In (Pausch et al, 1995) users hold a miniature model of the virtual world in one hand and manipulate objects in the miniature with the other. These systems employ only tracked wands or data gloves.

3 Device Prototypes and Software Integration

The YoYo is built using standard, off the shelf components. Two ergocommander units (the grip and sensor part of the Magellan space mouse) are used as elastic 6 DOF force sensors. A Polhemus Fastrack receiver is integrated into the center part and used for tracking the position and orientation of the device. Alternatively a source-less 3DOF isometric orientation sensor, the Intersense InertiaCube2 is used. This tracker derives its orientation from measuring the direction of gravity and the direction of the earth's magnetic field. Source-less tracking reduces setup time and improves handling considerably. The buttons on the device are either connected to the computer through a separate analog-digital converter or through the button inputs of the ErgoCommander® controllers.

We built two different versions of the device to experiment with differently shaped and sized centerpieces. Our first prototype used a box-shaped center piece (Figure 2). Six buttons were mounted on one side of the box. The size of the ErgoCommander® controllers is 65mm in diameter and 33mm height. The width of the box is about 40mm and the depth and height are 80mm. Each ErgoCommander® controller weighs about 50grams, and the center piece is around 70grams, which results in a total weight of 170grams. Four cables come off the device, one for each ErgoCommander® controller, one for the Polhemus sensor, and a separate cable for connecting the buttons to an external analog-digital connector.

Figure 2: The first YoYo prototype with a box-shaped center part.

Our second prototype (Figure 3) uses a cylindric centerpiece produced with stereolithography. The centerpiece has a slightly larger diameter of 68mm than the ergocommander grips and it is also slightly thicker (45mm) to hold an Intersense InertiaCube2 sensor. The total length of the device is 110mm and the weight is approximately 150grams.

The application integration on the device level is straightforward. Polhemus tracking sensors provide a matrix representing position and orientation of the sensor. The Intersense IC2 sensor delivers just an orientation matrix and no position information. The ErgoCommander® controllers allow 3mm linear elastic motion along each axis and 4 degrees of rotation. The output values of the sensors are proportional to the applied forces and moments.

Figure 3: The YoYo with a cylindric centerpiece and a single button.

We built the first device within a few days and integrated it into the Avango (formerly known as Avocado) graphics framework (Tramberend, 1999). Avango is based on SGI's Performer toolkit and OpenGL. We added a driver for the ergocommander units to the device driver layer of the system. The system supported already an analog/digital (A/D) converter, which we used to connect the buttons of the device to. Later we learned that the ErgoCommander® units also transfer the state of up to nine buttons, so for the second prototype we could reduce the number of cables to three. Most of the programming for the application integration was done in Scheme, Avango's scripting language. We used the device with a large cone-shaped 230 degree projection system, on a two-sided Responsive Workbench system (a Responsive Workbench with an additional vertical screen at the back), and in a monitor based environment.

4 INTERACTION SCENARIOS

The YoYo represents three coordinate systems shown in Figure 4. The central coordinate system represents the orientation and position of the device. The left and right coordinate systems represent the forces applied to the elastic sensors relative to the centerpiece. We integrated the device with two different interaction scenarios. The tube scenario maps the force input to the device directly to forces applied to a flexible model simulated by a real-time finite element simulation. The data visualization scenario demonstrates the use of the device for quasi-simultaneous navigation of the model and manipulation of data probes.

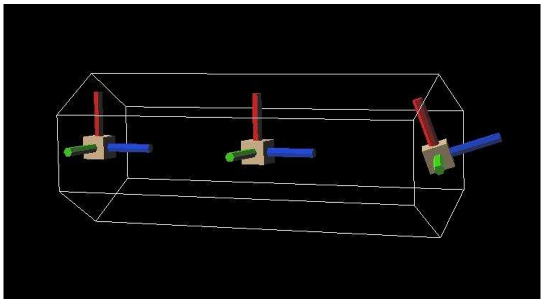

Figure 4: Three coordinate systems are represented by the YoYo.

4.1 The tube demo

In the tube demo, the YoYo is used to control input forces to a simulated linear elastic material. Here, position and orientation measured by the tracker in the center ring of the YoYo are directly connected to the global position and orientation of the tube. The two 6DOF elastic controllers of the YoYo are mapped to the ends of the tube, allowing the YoYo to act as a prop for the input of forces to the simulated tube (Figure 5).

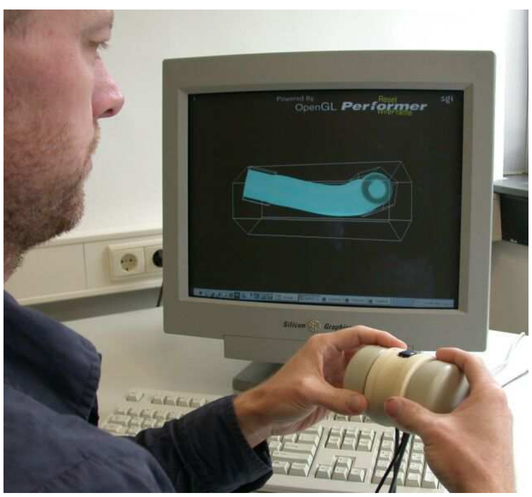

Figure 5: The YoYo controls the deformations of an elastic tube.

The real-time finite element simulation of the tube is done by precomputation of the Green's functions of the tube with respect to input forces to two handles at both ends of the tube (Nikitin et al, 2002). In the simulation, the motion of the handles of the tube is defined in the local coordinate system of the tube at rest. The reaction of the tube to the action on both handles is reconstructed as a linear combination of the Green's functions. This allows the simulation and maipulation of elastic material at interactive speeds.

The range of elastic motion of the ErgoCommander® is limited to ± 1.5mm for translation and ± 4° for rotation. In order to use the deflection of the controller as direct input for position and orientation of the handles of the tube, we are scaling these input values to produce effective motion. Translations are scaled relative to the length of the tube, so that maximum deflection by pushing in both sides of the YoYo completely squashes the tube and pulling effectively doubles its length. For rotation, we extend the range to ± 90°, exponentiating the original rotational input by 25. This range of motion allows bending the tube into U or S shape.

4.2 Cutting Plane Scenario

A basic task in scientific visualization is the exploration of data sets using data probes such as cutting planes and various types of lenses. For example, Hinkley(Hinckley et al, 1994a) uses a head prop and a cutting plane prop to explore volumetric data sets of human heads. We implemented interaction techniques, where the YoYo is used for a similar task. We use a model of a car or another object and a cutting plane for exploring the model (Figure 6). First, we describe our navigation techniques followed by manipulation techniques for cutting planes.

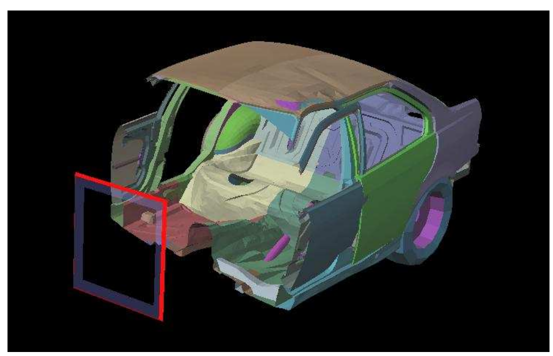

Figure 6: In this scenario, the YoYo controls position, orientation of the car model and the cutting plane.

4.2.1 Navigation around the model

We implemented two different variations for navigating our model, which use position-control and rate-control techniques. Scaling of the model is an integral part of navigation techniques.

Our first technique was implemented for the YoYo with the box-shaped center piece. In this version, the input device serves as a prop for the model. Props work best if the coordinate system of the data set and the coordinate system of the prop are always aligned. One of the buttons on the YoYo serves as a clutch, which attaches or detaches the YoYo from the dataset. The orientation of the dataset snaps to the orientation of the YoYo, when the clutch is engaged. We snap to the closest orientation of the YoYo to keep the snapping minimal, which avoids disorientation of the users. This is best explained by the following example: if the roof of the car is facing upwards and the YoYo's left controller also faces approximately upwards, we snap the model, such that the model's z-axis (axis through the roof) is exactly aligned with the YoYo's up facing axis. This general idea can be easily implemented using quaternions to express the angle between the coordinate system of the model and the 24 potential alignments with the YoYo. The z-axis of the model could be aligned with the YoYo's negative or positive x, y, or z axis and for each of these alignments, there are four possible orientations of model's coordinate system.

In this implementation, the orientation of the model is directly controlled by the orientation of the YoYo. For controlling the position of the data set, we use the input of the left ErgoCommander® controller with a rate-control mapping to achieve unlimited range. The translation inputs of the ErgoCommander® controller are transformed by the orientation of the YoYo, such that applying a force from the top moves the model down, applying a force from the left moves the model to the right, and so on. This orientation-corrected input results in an intuitive mapping. For increasing and decreasing the extent of the data set, we simply use two buttons on the device. In summary: this technique uses position control for controlling the orientation of the model, rate control for controlling the position of the model, and button-based rate-control for changing the scaling of the model.

Our second navigation technique abandons the concept of using the YoYo as a prop for the data set. We implemented this technique for the YoYo with the round center piece and the Intersense IC2 orientation tracker. Here, the orientation-corrected rotation input of the left ErgoCommander® is used for rate-controlling the orientation of the dataset. While pressing the single clutch button on the device, the orientation of the model is directly connected to the orientation of the YoYo. Here we do not use snapping, which results in a smooth attach/detach operation. Thus, the orientation can be controlled either by the ErgoCommander® or by the embedded rotation sensor. For translation of the model, we use the orientation-corrected translation input from the ErgoCommander®. For scaling the model, we use the input from both ErgoCommander® sensors. If the YoYo is squeezed, the model shrinks and if users pull at both sensors, the size of the model is increased. In summary: this technique uses position control *and* rate control for controlling the orientation of the model, rate control for controlling the position of the model, and rate-control for changing the scaling of the model.

4.2.2 Manipulation of a cutting plane

The cutting plane is always attached to the model and moves with the model during navigation. The right ErgoCommander® sensor manipulates the position and orientation of data probes exactly like the left sensor manipulates the position and orientation of the model – including the orientation correction. This distribution of tasks is very much in tune with Guiard's observations (Guiard, 1987), that the non-dominant hand provides a reference frame for the dominant hand's actions.

5 Experiences and Results

We have presented the YoYo to users on several occasions. The YoYo was shown to members of an oil and gas industry consortium, to a selected audience on a projection companies booth at Siggraph 2002, and at regular lab demos. We have also conducted an extended informal user test of the device with five participants

5.1 Data Visualization Scenario

We have used the YoYo with an application prototype for visualizing geo-scientific data. Here, we provide only a concise description of the scenario, since it is described in detail in (Fröhlich et al, 1999) and the scenario was also used with the initial version of the Cubic Mouse (Fröhlich et al, 2000a). The basic scenario consists of a volumetric data set – the seismic cube – and a set of polygonal surfaces within the volume data set. This data comprises the model. Within the model, there are data probes manipulated – such as cutting planes, axis-aligned and arbitrary oriented slices through the volume data, and volume lenses (Figure 7). The oil and gas data visualization requires also the positioning of three axis aligned slices. For this visualization mode, we move only one slice at a time by using only the largest translation input from the ErgoCommander® controller. This approach avoids drifting of the other slices, since elastic controllers deliver in almost all cases non-zero values for all three axes. Users switch between the different probes through a simple menu, which is activated and controlled by the buttons on the YoYo.

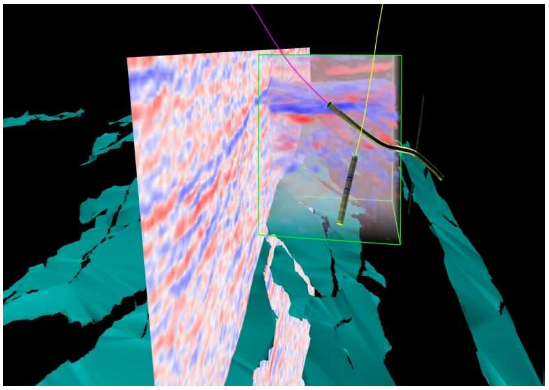

Figure 7: Visualization of oil and gas data set. A slice through the data set and a volume rendering lens are shown. The lines coming in from the top are wells. The green polygonal surfaces are surfaces separating two earth layers - so called horizons.

We use the YoYo with the box-shaped centerpiece and the interaction techniques described in the previous chapter for controlling this scenario. The box-shaped centerpiece serves as a prop for the seismic cube. The YoYo controls basically the same interactions that were previously used with the Cubic Mouse.

Ten participants of the VRGeo consortium had the opportunity to test the YoYo as an interaction device for the oil and gas demonstrator, using a large, immersive stereoscopic curved screen projection system. The device was used to navigate the model and to position different data probes within the data set. Trial time was limited to 2 to 5 minutes per participant. Almost all users were able to navigate and manipulate the dataset as they wanted. There were occasional problems with involuntarily moving the dataset out of view and sometimes users had to use multiple approaches to move the dataset or data probe into the desired position and orientation. Users liked the ability to navigate the dataset and to reposition the visualization tools quasi simultaneously. It was remarked that the rate controlled motion with the elastic controllers allows for smooth, controlled motion of the dataset.

5.2 Informal User Study

The YoYo was presented to five users (three male and two female, one with prior experience of using a SpaceMouse™, the stationary desk-top version of the ErgoCommander®) for an extended observed trial of about one hour. This extended trial time was given to get some feedback on the learning curve with elastic rate controlled interaction.

All participants had no problems using the device with very limited instruction, given by a demo showing the control of three independent coordinate systems with the device (see applications section).

All participants liked the directness of the mapping in the tube demo; they felt that it helped their understanding of the behavior of the device. While at first three of the five participants were using the device very coarsely, alternating between extreme twists and stretching of the tube, within minutes they started to experiment with differentiated small scale motion and more delicate dynamic effects, remarking "how sensitive the device reacts to touch". Two participants said they "wanted to make a ring" out of the tube (impossible because of the limited range in the mapping given by the demo and constraints on the linearity of the simulated material), one participant remarked that the YoYo allowed animating the tube to make "kind of a living worm".

The cutting plane demo allowed quasi-simultaneous manipulation of a cutting plane and navigation of the dataset. Position and orientation of the cutting plane was rate-controlled by one elastic controller of the YoYo. For navigation, two techniques were available: isotonic rotation of the dataset by pressing the clutch button and rotating the device; alternatively one of the elastic controllers allowed rate-controlled translation and rotation of the dataset. Scaling of the dataset was done by pushing and pulling both controllers at the same time.

None of the participants had trouble using the device or understanding the mappings of the controllers. All but one participant experimented for a short period with the handedness of the mapping; after five minutes or less they were using the dominant hand for manipulation of the cutting plane and the non-dominant hand for navigation with the elastic controller. All of them remarked that using the dominant hand for the manipulation of the cutting plane felt "more precise, more controlled". None of the participants was explicitly instructed to experiment with the handedness by turning the YoYo.

All participants continued to mix the use of isotonic control and elastic rate-control for object navigation, typically remarking that isotonic control was "more natural". However, elastic rate-control was used for "touching up" position and orientation. Rate-control was also used for large, sweeping motion, turning the object around completely. One user remarked that he preferred rate-controlled motion to “get an overview of the object”.

General remarks for shape, mapping and use of the device were collected. Two users particularly liked that the device felt “smooth” or “soft”. One user found the device too heavy. All remarked that the device reacted very delicately and sensitive to touch and small movement, requiring a substantial learning period. All participants said they enjoyed using the device, recognizing the long learning curve; one user saying that is was “fascinating; easy or not, I can’t decide, but it keeps you working with it”. All users remarked that the different mappings were easy and natural to use and remember, one user remarking “it is nice to be able to do all these things at the same time”.

6 Discussion

There are two main ideas behind the YoYo:

1. First, the device allows the quasi-simultaneous control of a large number of degrees of freedom in a single, compact device designed for two-handed operation. The YoYo enables the user to independently control three 6DOF coordinate systems.
2. Second, the device allows the use of elastic 6DOF force-input in a non-stationary device, suitable for use in large-scale virtual environments. It uses the tracked orientation of the device to align forces applied to the device and map them to absolute world coordinates.

For a number of common tasks in three-dimensional graphics applications, it is helpful to be able to control more than 6 degrees of freedom at one time. For data exploration, users have to navigate the data set, and they have to be able to adjust and move a cutting plane or lenses within the dataset – preferably without modal switching. This operation is supported by independent two-handed techniques, like in SmartScene(Mapes et al, 1995) or the two-handed prop-based techniques by Hinckley(Hinckley et al, 1994b), or by a complex device for two-handed operation like the CubicMouse™(Fröhlich et al, 2000a, 2000b). While independent two-handed techniques combine the use two 6DOF trackers, the CubicMouse™ uses a 6DOF tracker and tracking of position and rotation of three independent rods, also allowing the control of a second 6DOF coordinate system. The YoYo combines two 6DOF elastic controllers with a 6DOF tracker, allowing the independent control of three coordinate systems in a single device. Currently we use the control of the third coordinate system supported by the YoYo to enable users to choose between rate-control and isotonic control for navigation. This redundant mapping allows the user to choose the technique that is most suitable for the current situation and task.

While the use of isotonic techniques and direct manipulation lead in general to the most natural mappings for 6DOF manipulation, they have shortcomings that can limit their usefulness in virtual environments. Isotonic direct manipulation techniques suffer naturally from allowing only limited range. Rate-control techniques are significantly harder to learn, but they have a very large range, allowing fast and precise motion across several orders of magnitude. Isometric or elastic input techniques typically need only small motion and the application of small forces by the user, reducing fatigue and allowing the user to assume a comfortable position for long-term work. Elastic force input is also suitable for directly mapping input forces to simulated forces in a real-time physical simulation. This leads to a very realistic and responsive behavior of the simulation.

7 Conclusion and Future Work

We have developed a new handheld interface device, which combines elastic force input and isotonic input in a single compact unit. It allows intuitive quasi-simultaneous manipulation of graphical positioning, orientation, and scaling tasks by just changing the grip on the device. We experimented with two versions of the device in the context of visualization and simulation scenarios. Our user study and user observations show that elastic rate control and isotonic control for navigation is used in combination.

One other important task in graphical applications is pointing and selection. The YoYo with the round centerpiece has the shape of a pretty thick pointer, which make it suitable for these type of tasks as well. Smaller elastic sensors are just becoming available, which will turn the device into a more pen-shaped device.

The Intersense InertiaCube2 tracker is a sourceless orientation tracker, which has basically unlimited range. The tracking sensor and the ErgoCommander® units are connected to the computer through a serial interface, which can be made wireless using low power radio modems. In combination with smaller elastic sensors, this would result in a high degree of freedom device, which can be carried around in the pocket.

Our user tests show that novice users often have problems with elastic rate control at first, but manage to improve their skills already through the tests. Our experience with few expert users indicate, that there are in fact significant performance improvements possible. The arrangement of the elastic controllers and mapping of the inputs are generally perceived as very natural and easy to remember and use. These observations indicate the value of the device for novice and expert users by allowing for learning. The challenge is to explore the factors that influence the learning curve and develop devices and techniques with improved learning curves.

The YoYo is a first example of a device, where rate control and position control are used where it seems most appropriate by giving the user a choice using one or the other for the same task. Our work shows that there are a lot of options for designing three-dimensional input devices and it is worthwhile to explore different combinations of controllers and sensors in multi-degree-of-freedom devices.

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