The Quest for Intuitive 3D-Input Devices

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Abstract

This paper presents our approach for exploring the design space of input devices for three-dimensional graphics applications. We use an extended input device taxonomy as an inspiring source for generating permutations of sensors to suggest sensor configurations for new input devices. The taxonomy uses the integrated and separated degrees of freedom of an input device as a major classification criterion. We suggest and discuss input devices with six and twelve degrees of freedom, which are inspired by our taxonomy. By examining the properties of various devices and the different phases of a docking task, the idea for a new input device for large screen projection systems is derived.

1 Introduction

Interaction devices for three-dimensional graphics applications and virtual environments have evolved slowly. The desktop is still dominated by the mouse, even though more and more graphics applications are in regular use. For virtual environments, tracked wands and during the past years to a lesser degree gloves are the most often used input devices. Application developers often simply put up with these devices, since they are the only commercially available choices. They try to map their interaction tasks as best as possible to these devices, which results often in difficult to use interfaces and unnatural mappings.

The most common virtual reality display devices in real world applications in the industry are single or multi-projector walls or cylindrical screens. In most cases these systems are used in small groups and they are operated without head tracking or even in monoscopic mode. They are therefore less suited for direct interaction using gloves or wands. Even if head tracking is available, only one user is tracked, but it would be desirable to involve the other users into the interaction tasks as well.

In this paper we give an overview of some of our input device designs, which try to ameliorate some of the mentioned limitations. Some of our designs are based on a systematic exploration of the design space for multi-degree of freedom devices. This systematic approach is based on the classification scheme by (Jacob, Sibert, McFarlane & Mullen, 1994), which classifies devices according to their separable and integral degrees of freedom. Our approach uses a classification scheme or taxonomy to suggest new input devices instead of using it for classifying existing ones.

The challenge of input device design for 3D applications is to provide the perfect combinations of integral and separable degrees of freedom for a large variety of different tasks. This is probably impossible for a large number of general tasks. Most of the suggested device designs are well suited for certain tasks and less for others. Some devices are prop-based interfaces used in combination with two-handed interaction techniques, which have become increasingly popular. Passive real-world props augment interaction through tactile feedback and often lead to more intuitive interaction techniques. Alas prop-based interfaces are often very specific for certain tasks in an application and do not perform so well for a set of different tasks.

2 Systematic Exploration of the Design Space for Multi-DOF Devices

Sensors measure the users' inputs and they are the basic components for building input devices. There exists a large variety of sensors with different properties. One of the most relevant sensor properties for the design of input devices is the classification as isotonic, elastic, or isometric:

- **Isotonic** sensors require a constant force, which is often very low. A potentiometer is a common isotonic sensor. The standard mouse can be classified as an isotonic input device.
- **Elastic** sensors measure the applied force or torque and allow for some travel.
- **Isometric** sensors are force or torque sensors, but do not allow for travel.

The unexplored design space for input devices with 6 DOF and more is large. For each DOF, we have the choice of using isotonic, elastic, or isometric input sensors. Some of the sensors for the DOF could be integrated, others separated, which is usually a different way to express that certain DOF can be used simultaneously or not. The compatibility of the simultaneously available degrees of freedom of an input device with the integral attributes of a task can be seen as a major factor for the design of input devices (Jacob et al., 1994). An example: If a task requires movement in all three spatial directions, the input device should support these translations in multiple axes simultaneously. Therefore, to make and understand design decisions, one should also consider typical applications for the evaluation. This is especially the case for the multiple-DOF devices presented here, which are controlled by both hands.

For describing the different designs we introduce a notation, which abstracts the actually used sensors in an input device, but focuses on separate and integral degrees of freedom of the sensors. Some examples for integrated sensors for a certain number of degrees of freedom are the following: A potentiometer is a 1DOF sensor, an optical mouse sensor is an integral 2DOF sensor, an optically tracked point in space is a 3DOF sensor, the force and torque unit in a SpaceMouse is an integrated 6DOF sensor. An input device consists of one or more of these sensors, which we use as the characterization of the input device. By just looking at the possible combinations to achieve 6 DOF, we have already a lot of choices even though only a few 6-DOF devices exist. Besides the well known input devices such as integrated 6-DOF tracking sensors or the elastic 6-DOF SpaceMouse, there is the CAT and the old SGI Dial Box. The CAT (Hachet & Guitton 2002, 2003) is a 3 DOF + 3 DOF design, which combines isometric translational input with isotonic rotational input. The SGI dial box has 8 control knobs, which can be twisted. Six of the knobs can be used to perform 6 DOF translations and rotations. It is a 6 × 1 DOF design, since all of the knobs are equal and can be twisted individually.

2.1 6-DOF Devices

(Masliah & Milgram, 2000) and (Masliah, 2001) showed that users manipulate rotational and translational DOF as separate subsets in a 6-DOF docking task. Hence, input devices using separate sensors for the translational and rotational degrees of freedom have the potential to perform even better than integrated 6-DOF sensors, since they match the perceptual structure of the task. Based on this observation, one can generate a table for 6-DOF combinations from separate sensors. Even though integrated 3 DOF sensors for rotations and translation resulting in a 3 DOF + 3 DOF design might be the best choice, there are many more options available. These options might be better for other tasks than docking tasks or they are easier to manufacture or just cheaper to build.

Table 1: 6-DOF combinations of sensors based on separating translations and rotations into different sensors. Most combinations do not exist as an input device.

Trans DOF \ Rot DOF	3	2 + 1	3 × 1	2 × 1 + 1	1 + 1 + 1
3	CAT	°	°	°	°
2 + 1	°	°	°	°	°
3 × 1	°	°	dial box	°	°
2 × 1 + 1	°	°	°	°	°
1 + 1 + 1	°	°	°	°	°

There are many more combinations possible, which result in a total of six degrees of freedom. For example, navigation tasks often require combinations of rotations and translations. Walking or driving on a plane is perfectly supported by one or two translational and one rotational degree of freedom. A mouse, which also measures its orientation around the vertical axis would be an interesting device for these types of interaction tasks – at least if the application is controlled from the desktop.

The classification scheme could be also extended to reflect the types of sensors used. For example: isotonic degrees of freedom could be set as plain numbers, elastic DOF in italic, and isometric sensors as bold. The SpaceMouse uses an elastic *6* DOF sensor. The CAT would be 3 DOF + **3** DOF device. It is clear that this extended scheme classifies the devices more precisely, but it also adds complexity to the taxonomy. (Mackinlay, Card & Robertson, 1990) base their classification scheme also on the separation of force-sensors and isotonic sensors, but they also differentiate in addition between absolute and relative sensors. Our approach could also add this differentiation, but it would result just in a very large number of permutations, which are hard to interpret. Instead our approach suggests certain permutations of sensors with a certain number of DOFs and in a second step, real sensors may replace the abstract sensors in a suggested permutation. An example could be the combination of 6 DOF as 3 DOF + 2 DOF + 1 DOF sensors. The 3 DOF could be provided by an optical tracker, the 2 DOF by a trackball and the 1 DOF by a wheel. The translation would be absolute input through the optical tracker and the 2 DOF + 1 DOF are relative input for rotations. The spatial arrangements of the sensors which provide comfortable access to the six or more DOF are not considered by this scheme, but for the described case some configurations come immediately to mind. The trackball does not measure rotations around the vertical axis, thus it might be good to orient the wheel horizontally around the trackball.

(Balakrishnan, Baudel, Kurtenbach & Fitzmaurice, 1997) report that users perform mostly Euclidian movements with their Rockin'Mouse during the first phase of a 3-DOF docking task, which they call the ballistic phase of the task. During the final phase of the docking task, which is referred to as the "closed loop" phase, their subjects were fine tuning the position usually one dimension at a time. Based on (Jacob et al, 1994) one could interpret these observations as an indication that the ballistic and closed loop phase of the trial have a different perceptual structure. The ballistic phase requires the availability of integrated multi-degree of freedom sensors to allow for diagonal movements across the dimensions. The closed-loop phase may benefit from separately available DOF. These differentiation into coarse and fine movements suggests input devices, which support these very different input modalities. (Osawa and Ren, 2003) showed that using a data glove for the ballistic phase of a 3-DOF docking task and a 3D gearbox widget for the closed-loop phase performed better than each of the input modalities separately. The data glove allowed fast diagonal movements and the virtual gearbox widgets provided fine controls for each axis individually. Even though users had to switch between these input modalities, the overall task time was reduced. These observations motivate input devices with redundant degrees of freedom, for example a 6-DOF sensor combined with 6 × 1 DOF sensors. The 6-DOF sensor could be used for the ballistic phase, and the 6 × 1 DOF sensors could be used for the closed loop phase.

2.2 12-DOF Devices

The Cubic Mouse (Froehlich & Plate 2000) was the first input device, which integrates 12 DOF in a single unit. It is a cube-shaped box with three rods passing through it. The box is tracked and used for navigation tasks, whereas the rods can be pushed, pulled, and twisted to support object manipulation. The non-dominant hand controls the position and orientation of a virtual model and the rods are used to manipulate for example a cutting plane as shown in Figure 1. The Cubic Mouse is an isotonic device with a 6 DOF + 3 × 2 DOF design. The device is used with two hands. The axis separation provided by the three rods is well suited for the final – closed loop – phase in a docking task, where each axis is manipulated separately. During a 6-DOF docking tasks, the trajectory shown in Figure 2 was recorded. The trajectory shows the coarse movements during the ballistic phase of the docking task, the so called city-block motion, which is limited to one axis at a time due to the physical design of the Cubic Mouse. During the final phase of the docking task, the Cubic Mouse shows a very straight path in contrast to the data gloves, which produced a wiggly path. The data gloves performed well for the ballistic phase of the docking task, since they allowed diagonal movements. This observation confirms the results of (Osawa & Ren, 2003), who achieved the best results using a data glove for the ballistic phase of a docking task and a widget with single axis control for the final phase.

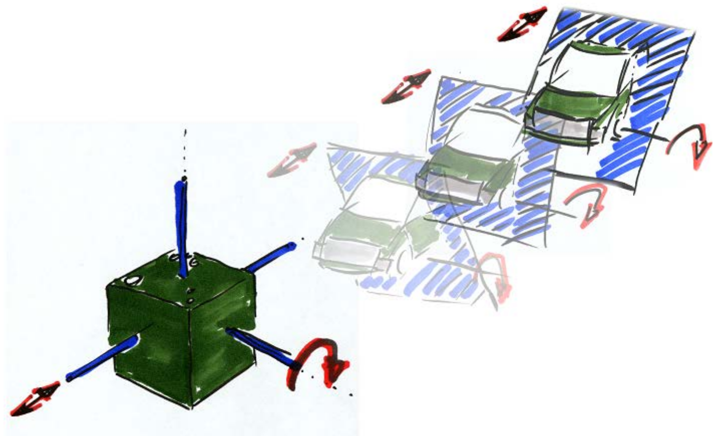

Figure 1: The Cubic Mouse

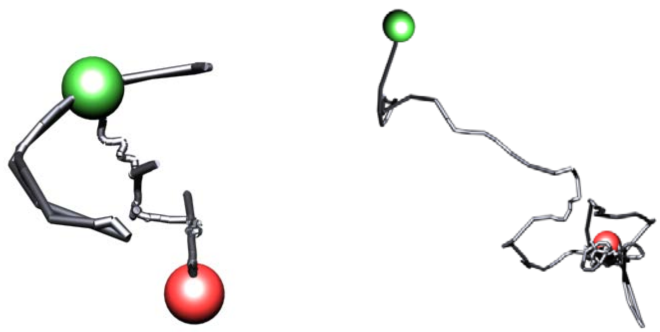

Figure 2: Representative trajectory visualizations for the Cubic Mouse (left) and data gloves (right). The green node represents the starting point, the red node the target in a 6-DOF docking task.

The design space for 12-DOF devices is much larger than for 6-DOF devices. A very large number of sensor configuration resulting in twelve or more DOF could be generated. However (Jacob et al., 1994) suggest, that only the integral and separable dimensions of a task need to be appropriately supported by the integral and separable DOF of an input device. The Cubic Mouse uses 6 DOF for navigation and 6 DOF for manipulation of objects. Our observations have shown that navigation and manipulation are basically not used simultaneously with this device. Thus it is reasonable to limit ourselves to two sets of 6 DOF sensor combinations, which results in a much smaller and easier to explore design space. Table 2 lists some potentially interesting combinations. Most of them are unexplored.

Table 2: Some 12-DOF combinations of sensors.

Navigation DOF \ Manipulation DOF	6	3 + 3	3 × 2	3 × 1 + 3 × 1	…
6	YoYo	°	Cubic Mouse	°	°
3 + 3	°	°	°	°	°
3 × 2	°	°	°	°	°
…	°	°	°	°	°

One of the devices that was inspired by thinking about possible sensor combination is the YoYo input device. The YoYo (Simon & Froehlich, 2003) consists of two elastic 6-DOF SpaceMouse sensors symmetrically attached to a grip in the middle as shown in Figure 3. This 2 × 6 DOF device is used with rate control techniques. The left

SpaceMouse is typically used for navigation, the right SpaceMouse for object manipulation – considering right handed individuals. Manipulations are performed by manipulating the caps of the SpaceMouse sensors on the left or right side. Switching between navigation and manipulation requires changing the grip on the device. Often a 6-DOF tracker is embedded in the grip. This configuration could be classified as a 6 DOF + 2 × 6 DOF device resulting in an 18 DOF device. This large number of DOF is used to provide redundant DOF for example for isotonic position-controlled rotation using the tracker as an alternative to the elastic rate-controlled rotation of the SpaceMouse sensors. The tracker can also be used to compensate for rotations of the YoYo against the world coordinate system. In this case the DOF of the tracker support the other DOF of the SpaceMouse sensors and they are not explicitly available to the user.

Figure 3: The YoYo consists of two SpaceMouse sensors attached to a grip in the middle

The idea for the YoYo resulted from a discussion about sensor combination to achieve twelve degrees of freedom. The discussion was inspired by the 12 DOF in the Cubic Mouse. The most straight forward combinations are two 6-DOF sensors, for example a tracker and a SpaceMouse sensor. A tracked SpaceMouse could be used in a similar way as the Cubic Mouse. The tracker could be used for navigation tasks and the SpaceMouse for object manipulation tasks. The second SpaceMouse sensor was added for symmetry reasons first, but later took over a major role as an input channel for navigation. The non-dominant hand navigates using one SpaceMouse and the dominant hand manipulates an object by using the other SpaceMouse sensor.

3 Multi-Degree of Freedom Input Devices

Several devices allowing for 3D interaction have already been developed. They can be distinguished according to various features (e.g., Buxton 1983, 1990; Jacob et al. 1994). As already mentioned, the integrality or separability of the DOF in a task is one important characteristic (Jacob et al., 1994), which should be appropriately supported by the input device. Other features are the types of sensors used in the input device (isotonic, isometric, elastic), and the types of transfer functions (position control, rate control) used in the application. Previous work has already shown that the combinations of isotonic devices with position control and of elastic or isometric devices with rate control are superior over other combinations (Zhai, 1995).

The “Bat” (Ware, 1990) consists of an electro-magnetic tracking sensor, a button, and a handle. The device is mainly used for isotonic position control. The EGG (Elastic General purpose Grip) (Zhai, 1995) is basically a handle suspended in the air by a set of elastic springs. The position and the orientation of the handle are tracked by an electromagnetic tracker. This 1 × 6 DOF device with elastic input for all six DOF is conceptually similar to a SpaceMouse, but allows larger travel. The Fball or Fingerball (Zhai, 1995) is a ball-shaped input device containing an electromagnetic tracking sensor. This isotonic device is designed to be rolled with the fingertips to support dexterous rotational input.

(Balakrishnan et al., 1997) developed the Rockin’ mouse, a 4-DOF device which seems like a 2 DOF + 2 DOF design at first. 2 DOF are provided by the planar movement of the device and the additional 2 DOF are provided by the tilt (“rockin’”) of the device. This device was compared to a regular mouse in a 3D positioning task. One tilt-DOF of the Rockin´ mouse was not used. The Rockin´ mouse outperformed the standard mouse which required to switch between moving in the different 3D planes. It was also shown that the 3 DOF of the device were used simultaneously despite the asymmetric design of the DOF. The Rockin' mouse would be an interesting candidate for adding further 2 or 3 DOF to turn it into a full 6 DOF device.

The 6 DOF SpaceMouse and SpaceBall as well as some derivations of them are currently the only commercially available 6-DOF desktop devices. They are controlled through a ball (SpaceBall) or a puck-shaped handle (SpaceMouse) which can be translated and twisted using force. These isometric (SpaceBall) or elastic (SpaceMouse) devices are typically used with rate control techniques. Both devices are employed in the CAD industry. One reason why they nevertheless still lack acceptance is probably that their design uses rate control which has been shown to be harder to use, at least for novice users (Zhai & Milgram 1998). In addition, the use of an integrated 6-DOF sensor leads to several unintended object movements: Since all 6 DOF are integrated in one controller, often translations produce slight rotations and vice versa. The controller used in a SpaceMouse is also available separately and can be used for building custom input devices such as the YoYo (Simon & Froehlich, 2003).

4 New Multi-Degree of Freedom Devices

We present some devices that were inspired by the introduced taxonomy or by a task analysis with respect to the integral and separable dimensions of a task. We focus on hand-held devices, which are mostly required for interactions in virtual environments.

4.1 Hand-held 6-DOF Devices

Pointing devices for virtual environments are typically built using a tracker embedded into a wand, which is equipped with a few buttons. However, human hands can only provide very constrained 6 DOF input. For example movements away from the user are very limited as well as rotations around the different axes. The hand and the arm are very good at pointing and moving something across a screen - from left to right and bottom to top and back. The pointing part is basically a 2-DOF operation relative to the user's position. The movement in depth should preferably provide an extended or even unlimited range. Here non-isomorphic arm extension techniques like the Go-Go interaction (Poupyrev et al 1996) could help. Alternatively, the input device could provide a separate 1 DOF sensor for depth movements, such as a joystick with a centering mechanism, which could be used with rate control techniques. An alternative to the direct use of the actual hand rotations, is the use of an appropriate sensor for the rotations: a 3-DOF joystick, a 3-DOF trackball or a SpaceMouse are some possibilities. Based on these thoughts, we are able classify such an input device as a 2 DOF + 1 DOF + 3 DOF design. For the two DOF pointing operation, a two axis gyroscope could be used instead of an electromagnetic or optical tracker, at least if a fixed hand position can be assumed. Two axis gyroscopes are used in various handheld pointing devices for controlling desktop applications displayed on projection screens. The disadvantage of these readily available sensors are that they report only relative movements. Two suggestions for input devices based on a 2 DOF + 1 DOF + 3 DOF design are shown in Figure 4. Figure 5 shows an actual prototype of one of the devices.

First tests in a 3D docking task application revealed some interesting properties of the new device. Selection of virtual objects and the ballistic first phase of the docking task worked really well. The cursor object, which needs to be docked onto the target, is positioned quickly close to the target. Even though the translational positioning is a 3-DOF task, the 2 DOF + 1 DOF design used in this device works quite well and with some experience the resulting 3 DOF can be used simultaneously. However, for the last phase of the docking task, when the fine positional adjustments need to be made, the 2-DOF pointing mode does not work so well – especially for objects farther away from the user. The rate-controlled 1-DOF translation provides much finer control and it is easier to use. Users expressed even that they would prefer to have a joystick for the other translational axes as well to do the fine translational adjustments. Again, this would introduce redundant degrees of freedom, which seem to be useful for the different phases during an interaction. The rotation is well supported by a 3-DOF joystick, which has to be operated by the non-dominant hand.

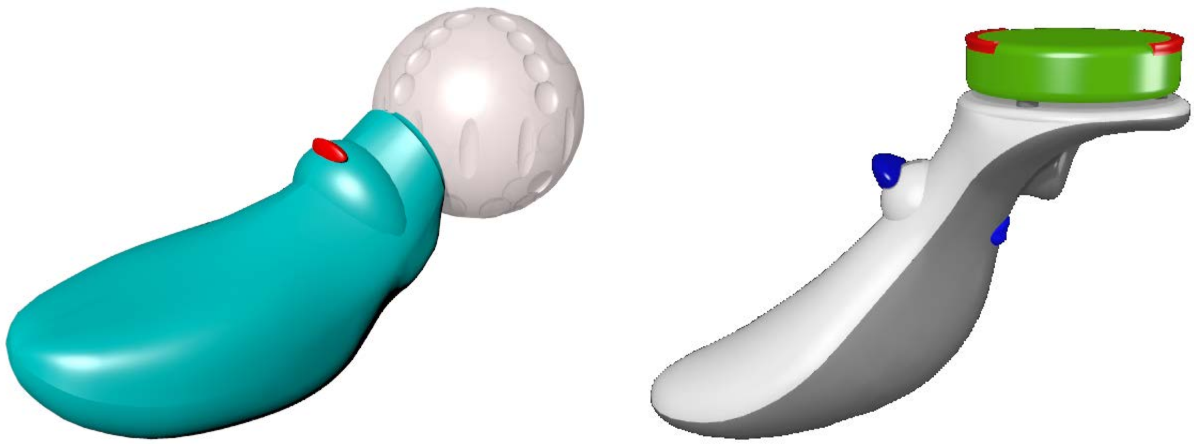

Figure 4: Two input devices for selection and 6-DOF manipulation tasks. The body of the device is tracked or contains at least a 2 DOF orientation sensor. The small red knob in the left figure and the small blue knob in the right figure are 1-DOF joysticks. The white ball in the left figure contains a 3-DOF joystick, which is operated with the non-dominant hand to specify rotations. In the right figure the green SpaceMouse controller on the top can be used for specifying rotations.

Figure 5: An actual prototype of the device in Figure 4. The device consists of a two axis gyroscope inside the handle, a 1-DOF joystick operated by the thumb, and 3-DOF joystick inside the ball.

4.2 Hand-held 12-DOF Devices

We have further developed the idea of the YoYo devices and also developed a variation of the Cubic Mouse, which is called the Cubic SpaceMouse.

4.2.1 Two new members of the YoYo family

The so called Round Bone (Figure 5) belongs to the YoYo family and consists of two 6-DOF SpaceMouse sensors similar to the original YoYo. The caps of the SpaceMouse sensors are removed and round handles are mounted instead. These handles are manipulated with the fingertips – potentially simultaneously by both hands. The round bone has its' grip on the outside and rests comfortably in the user's hands. This is the main advantage and difference compared to the original YoYo device. The Tire is basically a Round Bone with only one SpaceMouse sensor – thus providing only 6 DOF which are typically controlled with the dominant hand. A toggle button is used to switch between navigation tasks and object manipulation. An initial comparison of these devices with the original YoYo revealed that the Tire performs in general worse than the YoYo and the Round Bone, which perform on an equal level. As a test case, we looked at a docking task, which required object manipulation as well as navigation. The reason for these results seem to be that the Tire requires explicit switching between navigation and object manipulations. These are just first impressions, which need to be confirmed by an extended study.

Figure 6: The Round Bone (left) and the Tire (right). Both devices are built from elastic SpaceMouse sensors.

4.2.2 The Cubic SpaceMouse

The Cubic SpaceMouse is an input device, which tries to combine the properties of the Cubic Mouse and the SpaceMouse in a single device. The Cubic Mouse has the problem that the rods require clutching if they arrive at their stop. The SpaceMouse is an elastic force sensor and does not require clutching when used with rate control techniques. Figure 7 shows some drawings of the device. A SpaceMouse sensor is encased in a cube-shaped box and rods are attached to the six sides of the SpaceMouse. Inside the box there is additionally an electromagnetic tracking sensor embedded. Looking at the sensors, this is clearly 6 DOF + 6 DOF design, but from the user's point of view, it is different. Each of rods can be pushed, pulled, and twisted. In addition, each rod can be operated like a joystick (see Figure 8), which can be used for example for rate-controlled navigation tasks. Thus each rod provides 4 DOF. For the user, the device appears like a 6 DOF + 6 × 4 DOF design, but the degrees of freedom of the different rods are not independent. They can be either used in a redundant and consistent way or the actually used rod needs to be identified by the software. If the used rod can be identified and only one rod is used at a time, the device provides virtually independent 6 × 4 DOF through the rods. We actually built two prototypes of the device. The latest prototype is shown in Figure 7. In our version, we could not identify, which rod was actually used during the interaction. Initial tests of the device revealed, that in most cases it was harder to use than the original Cubic Mouse. The reasons were the complex coupling of the movements of the rods with the affected degrees of freedom in particular when using the joystick mode.

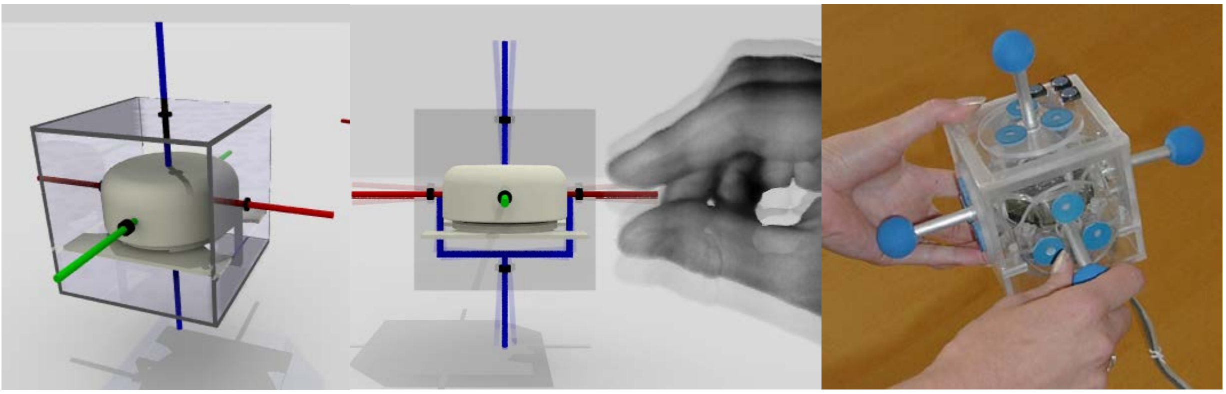

Figure 7: Studies of the Cubic SpaceMouse and the actual prototype on the right

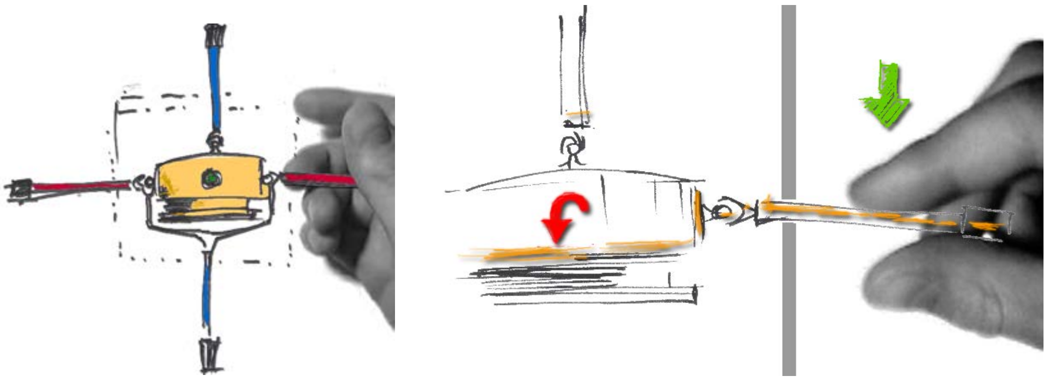

Figure 8: Interactions with the Cubic SpaceMouse. In addition to pushing, pulling, and twisting the rods (left), the device also allows for a joystick like interaction (right).

5 Conclusion and Future Work

We have presented some of our ideas for designing multi-degree of freedom input devices. We used a taxonomy introduced by (Jacob et al., 1994) as a tool to suggest sensor combination for new input devices. Some of these combinations were actually built and initially tested with basic application scenarios. We have also introduced the concept of redundant degrees of freedom in an input device to support different phases of a task. The unexplored design space for multi-degree of freedom input devices is still very large. Further user studies based on carefully selected tasks need to examine the advantages and disadvantages of various integrated and separated solutions in order to suggest the most promising combinations. However, one major challenge is to find spatial arrangements of sensors which provide comfortable access to the six or more DOF in a single device.

Currently most systems support only single user interactions. Only recently virtual reality systems supporting multiple tracked users (Froehlich et al., 2004) have been introduced. Such systems are able to support true multi-viewer interaction. Each user may participate with an input device in the interaction with the application, which provides many challenges for the design of the appropriate devices and interaction techniques.

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7 References

Balakrishnan, R., Baudel, T., Kurtenbach, G., and Fitzmaurice, G. 1997. The Rockin´ Mouse: integral 3D manipulation in a plane. SIGCHI proceedings, 311-318.

Buxton, W. (1983). Lexical and Pragmatic Considerations of Input Structures. Computer Graphics, 17, 31-37.

Buxton, W. (1990). A Three-State Model of Graphical Input. In D. Diaper et al. (Eds), *Human-Computer Interaction - INTERACT '90*. Amsterdam: Elsevier Science Publishers B.V. (North-Holland), 449-456.

Froehlich, B. and Plate, J. (2000). The Cubic Mouse: A new device for 3D input, Proceedings ACM CHI 2000, 526-531.

Froehlich, B., Hoffmann J., Klueger, K. & Hochstrate J. (2004). Implementing Multi-Viewer Time-Sequential Stereo Displays Based on Shuttered LCD Projectors, 4. Immersive Projection Technology Workshop, Ames, Iowa, May 2004.

Hachet, M. & Guitton, P. (2002). The Interaction Table - a New Input Device Designed for Interaction in Immersive Large Display Environments, Proceedings 8th Eurographics Workshop on Virtual Environments 2002, 189-196.

Hachet, M., Guitton, P., & Reuter, P. (2003). The CAT for efficient 2D and 3D interactions as an alternative to mouse adaptations. Proceedings VRST 2003, 205-212.

Jacob, R. J. K., & Sibert, L. E. (1992). The perceptual structure of multidimensional input device selection. Proceedings of the CHI '92 Conference on Human Factors in Computing Systems, 211-218.

Jacob, R. J. K., Sibert, L. E., McFarlane, D. C., & Mullen, M. P. (1994). Integrality and separability of input devices. *ACM Transactions on Computer-Human Interaction, 1, 1*, 3-26.

Mackinlay, J. D., Card, S. K. & Robertson, G. G. (1990). A Semantic Analysis of the Design Space of Input Devices. *Human-Computer Interaction* 5(2-3): 145-190.

Masliah, M. & Milgram P. (2000). Measuring the allocation of control in a 6 degree-of-freedom docking experiment, Proceedings ACM CHI 2000, 25-32.

Masliah, M. (2001). Measuring the allocation of control in 6 degree of freedom human-computer interaction tasks, PhD thesis, University of Toronto.

Osawa N. & Ren X. (2003) An Evaluation on Approximate and Fine Adjustments by Hand Motion in an Immersive Environment, 9th International Conference on Virtual Systems and MultiMedia 2003 (VSMM2003), pp.322-329.

Simon, A. & Froehlich, B. (2003). "The YoYo: A Handheld Device Combining Elastic and Isotonic Input", Interact 2003, 303-311.

Zhai, S. (1995). Human Performance in Six Degree of Freedom Input Control, PhD thesis, University of Toronto.

Zhai, S. & Milgram, P. (1998). Quantifying Coordination in Multiple DOF Movement and Its Application to Evaluating 6 DOF Input Devices, Proceedings of the Conference on Human Factors in Computing Systems CHI 1998, 320-327.