The GlobeFish and the GlobeMouse:
Two New Six Degree of Freedom Input Devices for Graphics Applications

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ABSTRACT
We introduce two new six degree of freedom desktop input devices based on the key concept of combining forceless isotonic rotational input with force-requiring elastic translational input. The GlobeFish consists of a custom three degrees of freedom trackball which is elastically connected to a frame. The trackball is accessible from the top and bottom and can be moved slightly in all spatial directions by using force. The GlobeMouse device works in a similar way. Here the trackball is placed on top of a movable base, which requires to change the grip on the device to switch between rotating the trackball and moving the base.

Our devices are manipulated with the fingertips allowing precise interaction with virtual objects. The elastic translation allows uniform input for all three axes and the isotonic trackball provides a natural mapping for rotations. Our user study revealed that the new devices perform significantly better in a docking task in comparison to the SpaceMouse, an integrated six degrees of freedom controller. Subjective data confirmed these results.

Author Keywords
User interface hardware, input devices, interaction techniques, human factors.

ACM Classification Keywords
H.5.2 [User Interfaces and Presentation] User Interfaces: Input devices and strategies.

INTRODUCTION
Graphics applications for desktop environments often support six degree of freedom (6-DOF) input devices to facilitate three-dimensional (3D) navigation and manipulation. Currently, there are mainly two commercially available 6-DOF desktop devices used: the SpaceMouse™ and the SpaceBall™ [3dconnexion.de]. Both devices are force and torque sensors. Whereas the SpaceBall is close to a purely isometric device with only very little travel, the SpaceMouse is an elastic device with a self-centering mechanism. Both devices are used with rate control techniques and have integrated 6-DOF sensors with the disadvantage that translations often induce slight rotations and vice versa. To avoid these problems, some users switch the device into a mode which makes use of only the strongest translational or rotational component.

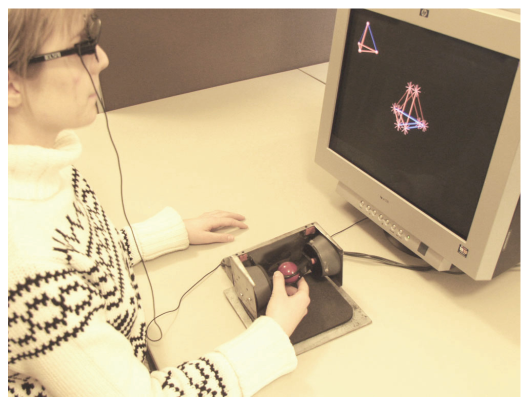

Figure 1: A participant of our study using the GlobeFish in a 3D docking task.

According to Jacob et al. [9], one central feature contributing to the usability of a device is its compatibility to separate and integral attributes of the task. Typical tasks in 3D environments require 6-DOF docking [12,17,18]. One might expect that translations and rotations in three dimensions are perceptually integral attributes thus requiring an integrated 6-DOF device, but Masliah et al. [12,13] showed that users manipulate rotational and translational DOF as separate subsets in a 6-DOF docking task. Hence, input devices providing separate controls for translation and rotation can be assumed to perform better than an integrated 6-DOF controller.

We present two new 6-DOF desktop input devices – the GlobeFish and the GlobeMouse (see Figure 1). These devices separate rotational and translational input and implement a 3 DOF + 3 DOF design. The GlobeFish consists of a custom 3-DOF trackball suspended in an elastically connected frame. The trackball is accessible from the top and bottom and can be moved slightly in all spatial directions by using force. It is self-centering when no force is applied. The GlobeMouse features a trackball placed on top of a SpaceMouse. It is therefore a hybrid between the GlobeFish and the SpaceMouse. This design requires a grip change for switching from rotating the trackball to moving the base. Both devices are manipulated with the fingertips allowing precise interaction with virtual objects.

The combination of a trackball with elastic or isometric input for translations effectively decouples forceless rotations from force-requiring translations and provides a clear separation between these input modalities. In addition the elastic translational input allows a uniform treatment of the three translational axes, while the 3-DOF trackball is a natural mapping for rotations. Our user study compares the GlobeMouse and two variations of the GlobeFish to the commercially available SpaceMouse. The results show significant performance advantages of more than 20% for our new devices over the SpaceMouse in a 3D docking task. The data indicates that this is mainly due to the more efficient isotonic trackball rotation. This is confirmed by subjective reports in which users clearly preferred our devices in many aspects in comparison to the SpaceMouse.

INPUT DEVICES PROVIDING MULTIPLE DOF

Several devices allowing for 3D interaction have been developed. They can be distinguished according to various features [2,3,9]. As already mentioned, the integrality or separability of the DOF in a task is one important characteristic [9] which should be appropriately supported by the input device. For 6 DOF, one can differentiate between 1 * 6 DOF (e.g., the SpaceMouse), 3 DOF + 3 DOF (e.g., our new devices), 6 * 1 DOF, or other combinations (e.g., 5 + 1 DOF, 3 + 2 + 1 DOF). The types of sensors used for the design of input devices are very important and they are often classified in the following way:

- *Isotonic* sensors measure the travel and require a constant – often very low – force for being moved.
- *Elastic* sensors allow for some travel and provide a counterforce which increases with travel distance.
- *Isometric* sensors measure force or torque, but do not allow for travel.

Transfer functions interpret a sensor's output and transform it into the movement of an object in an application. Two types of transfer functions are commonly used:

- *Position control* transforms the sensor reading into a displacement of the graphical object. In the easiest case a linear relationship between sensor value and object displacement is used, but non-linear transfer functions are common.
- *Rate control* converts the sensor reading into the velocity of a graphical object.

Previous work has shown that the combinations of isotonic devices with position control and of elastic and isometric devices with rate control are superior over other combinations [17]. With respect to 6-DOF devices designed for desktop environments, uni-manual control is certainly a desired feature. The use of a position tracker for the translational DOF requires the lifting of the device off the desk, which might be fatiguing. In addition, the use of a clutch is often unavoidable to cover a large translational range.
The CAT [5,6] is a free-standing 6-DOF input device, which uses isometric input for translations and isotonic input for rotations. This 3 DOF + 3 DOF-device is used with two hands by holding on to a plate, which can be rotated around the three spatial axes. Directional forces applied to the plate are also measured and used for isometric input. Due to the mechanical design and the nested axes of the device some rotations and translations are difficult to perform. The device was designed for large screen environments and would be difficult to adapt to desktop environments and uni-manual control.

The same arguments hold for the Cubic Mouse [4], 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 Cubic Mouse is an isotonic device with a 6 DOF + 3*2 DOF design. The device is used with two hands and requires some space due to its size. Both requirements are hard to fulfill in desktop environments.

The "Bat" [16] 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) [17] 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 for larger travel. The Fball or Fingerball [17] is a ball-shaped input device containing an electromagnetic tracking sensor. This isotonic device is designed to be rolled with the fingertips to support precise rotational input.

The Rockin' mouse [1] is 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 switching between translation within the three axis-aligned planes. It was also shown that the 3 DOF of the device were used simultaneously despite the asymmetric design of the DOF. Adding further 2 or 3 DOF would turn the Rockin´mouse into a full 6-DOF device with promising capabilities.

A 6-DOF device supporting isotonic rotation is the Inspector mouse [dimentor.com]. This 2-DOF mouse is equipped with a scroll wheel, which might be used for translation in z-direction. A 3-DOF trackball is mounted on the back of the mouse. Thus the device combines 2 + 1 isotonic translational DOF with 3 isotonic rotational DOF. Unfortunately, this device is not sold any more, nor are there, to our knowledge, any studies providing information about its performance. It can, however, be assumed that the use of the scroll wheel for z-translations might be tiring. Alternatively, a modifier key can be used for mapping one of the mouse axes to z-translation, but in both cases the separation of the z-translation from the x- and y-translation prohibits simultaneous 3D control. The design also requires a grip change to switch between translation and rotation, similar to the GlobeMouse.

The 1 * 6 DOF SpaceMouse and SpaceBall as well as some derivations of them are currently the only commercially available 6-DOF desktop devices [3dconnexion.de]. These one-handed devices 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 [18]. 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 induce slight rotations and vice versa.

DESIGN DECISIONS

Our main goal was to design an easy to use desktop input device for 3D graphics applications. Based on Masliah´s observations [12] that the rotational and translational degrees of freedom are almost always manipulated separately, we decided to explore the possibilities for a 3 DOF + 3 DOF design. One important characteristic for a 3-DOF subset are the types of control – isometric/elastic vs. isotonic.

Zhai [17] observed equal performance for 6-DOF isotonic input using a tracked glove compared to isometric input using a SpaceBall. Only for novice users, the glove performed slightly better. On the other hand, a tracked ball-shaped input device manipulated with the finger tips was shown to perform better than the tracked glove [17]. There are some indications that this improvement can be mostly attributed to the facilitation of rotations using the fine muscle groups of the fingers. In addition, Kim et al. showed that a 3-DOF trackball performs better for pure rotational tasks than a SpaceMouse [10]. Thus, isotonic rotation involving the fingers appears to be better than other forms of rotation. In addition, using the rotation of a trackball to control the rotation of a virtual object seems to be the most natural mapping.

As already mentioned, using a position tracker for controlling 3-DOF translation in a desktop environment requires lifting the device off the surface of the desk or keeping the arm suspended in the air. Both are fatiguing after a short period of time. One alternative might be a design similar to the Rockin' mouse [1] which uses tilting of the mouse as z-translation. Although users of the Rockin´ mouse were able to use all three DOF simultaneously and could achieve an advantage over a 2D mouse and widgets, this mapping is not particularly intuitive and requires learning. Another possibility is the separation of the DOF – similar to the Inspector Mouse – into for example a 2 DOF + 1 DOF design. This design, however, does not allow for integral 3D translation, which is of advantage as shown in [1]. To achieve a uniform treatment of all the axes, we decided to use an elastic 3-DOF sensor for translation.

DEVICE PROTOTYPES

The GlobeFishes

The design of our GlobeFishes is based on the key concept of embedding a 3-DOF trackball in an elastic frame thus combining isotonic rotations with elastic translations. Rotations are performed by rotating the trackball and translations are performed through the trackball as well by a slight firming of the grip.

We have built a variety of prototypes of our GlobeFish devices. The very first prototype (shown in Figure 2) is a 5-DOF version offering only 2 translational DOF. After further testing, we arrived at two designs: the small GlobeFish and the large GlobeFish. Their main differences are their tracking solutions and the accessibility and size of the 3-DOF trackball.

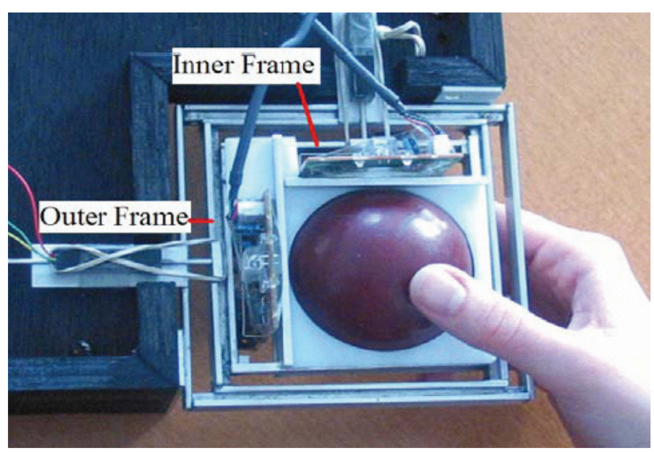

Figure 2. The first GlobeFish prototype uses two nested frames to track 2-DOF translations. The outer frame moves left and right, the inner one up and down. The movements are tracked with spring loaded potentiometers. Trackball rotations are measured by two optical mouse sensors.

Our GlobeFish devices use a 3 DOF + 3 DOF design based on two integrated 3-DOF sensors – the 3-DOF trackball unit and a SpaceMouse controller or three potentiometers providing the translation measurements. Within the rotational and translational subsets, users can manipulate all 3 DOF simultaneously. Combinations of translations and rotations are possible as well, but are limited to small rotations and the combination of certain axes.

The Small GlobeFish

The small GlobeFish (Figure 3) employs a 40mm trackball mounted between two rings such that the ball rotates freely in all directions. The actual rotations of the ball are measured by two commercially available optical trackball sensors mounted between the two rings behind the ball. The sensors are perpendicular to each other to achieve the best precision as also suggested by [10]. The optical trackball sensor units are connected to the computer using the provided USB cables. We wrote a custom driver to support two simultaneous trackball inputs in our test applications.

The mounting rings of the ball are elastically connected to an external frame. This setup allows small translations of the ball in all spatial directions. A SpaceMouse sensor mounted in the left socket is used to measure these translations. The right socket contains counterbalancing springs. This setup requires twice the amount of force as a standard SpaceMouse.

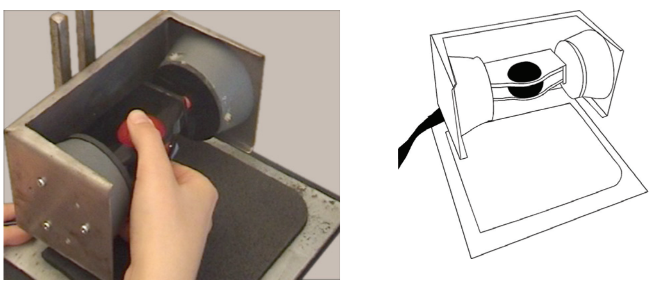

Figure 3: The small GlobeFish uses a 40mm trackball which is accessible from the top and bottom

During interaction tasks, the hand stands upwards. The ball is accessible from the top and bottom. The thumb typically rests on the top and index and middle finger manipulate the trackball from the bottom, which allows comfortable 3-DOF rotations by just using the fingertips. Translations require just a slight firming of the grip on the trackball and a push or pull into the appropriate direction. They may additionally need small wrist movements. By making use of only the fingers and the wrist, the most dexterous muscle groups are involved [11].

The Large GlobeFish

The large GlobeFish (Figure 4) features a 55mm trackball and a mechanical tracking system for measuring translations. The rotations of the trackball are captured using two optical mouse sensor units. The trackball is accessible from the top and bottom as well as partially around the equator. This prototype uses three nested frames to implement the translational degrees of freedom. Each frame can be moved along one of the spatial axes. Three potentiometers were used to measure the movements of the nested frames and springs provided the self centering mechanism. The inputs from the potentiometers for this prototype were captured using a custom analog-digital converter, which provides ten bit resolution.

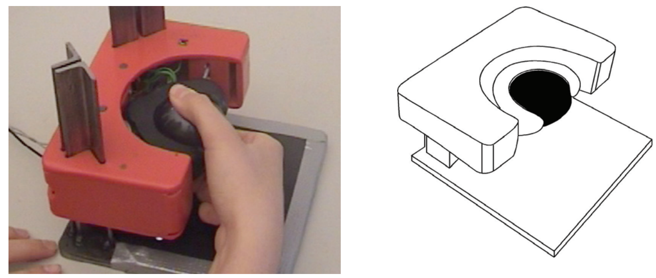

Figure 4: T he large GlobeFish consists of a mechanical tracking system and a 55mm trackball.

The mechanical construction of three nested frames would require precise manufacturing methods, which were beyond our current capabilities. Our prototype worked reasonably well at the beginning of our user study, but the smoothness of translational movements deteriorated after a number of trials. The frames got partially stuck thus impairing the self-centering mechanism. Nevertheless, the large trackball and its accessibility around the equator were positively mentioned by several participants testing the device.

The GlobeMouse

The GlobeMouse (Figure 5) is a hybrid between a GlobeFish and a SpaceMouse. A 3-DOF trackball rests on top of a SpaceMouse unit. The rotational input from the SpaceMouse is currently ignored, but could be used to provide three further elastic DOF. We replaced the cap of the SpaceMouse by a box-shaped enclosure to provide space for the two optical sensors for the trackball. This additionally provides a tactile coordinate system for translations which is supported by the black pads centered on each of the four sides of the handle. One main advantage of this setup is the good accessibility of the trackball. However, one limitation is that one has to change the grip on the device to switch between rotation and translation.

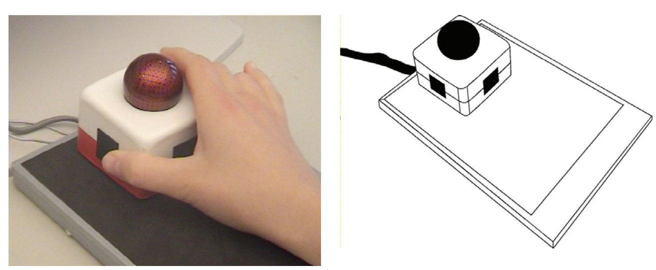

Figure 5: The GlobeMouse uses a trackball on top of a SpaceMouse sensor. Switching between rotations and translations requires a grip change.

USER STUDY

Performances of input devices providing multiple DOF are determined using various tasks and various baselines. For 6-DOF devices, typical 3D tasks examine either tracking [19] or docking performance [18,19]. We implemented the 3D docking task developed by [19]. Within this task, a 3D cursor has to be docked onto a 3D target thus investigating rotation and translation performance simultaneously. Since the GlobeMouse requires grip changes to switch between both, the costs of re-grasping can be assessed by this task. At the same time, this task not only enables us to determine general performance, but also to separately study rotation and translation performances. Our study uses an established task, which relates our results to previous work. Only recently an extended docking task involving a combination of spatial navigation and object manipulation was introduced [8]. Such a task is closer to a real-world scenario and it could be used for a follow up study. Other more complex task combinations involving a variety of different desktop activities in addition to 3D tasks have not been established and they would be very difficult to evaluate.

The choice of a suitable baseline comparison was more difficult. Unfortunately, an Inspector mouse providing six isotonic DOF was not available to us. The 2-DOF mouse requires to combine the device with the keyboard by using several modifier keys or with widgets for selecting a mapping of the 2 DOF to a subset of the 6 DOF. Hinckley et al. [7] showed that integral 3D control for a 3D rotational matching task performed significantly better than 2D techniques using a 2D mouse. Balakrishnan et al. [1] arrived at a similar conclusion for 3D translational tasks. As already pointed out, the SpaceBall, the SpaceMouse and some derivates are the only commercially available devices developed for 3D applications. Kim et al. [10] compared their 3D trackball to a SpaceMouse in a rotation only task. Our extension of this concept in providing all 6 DOF suggests to compare performances to the elastic SpaceMouse as well.

Methods

Participants

16 users, all of them reported to be right-handed, volunteered to participate in the study. All participants had stereo vision capabilities shown by the fact that they perceived the stereoscopically presented target position at least 8 cm in front of the monitor.

Stimuli

For each device, sensitivity thresholds as well as sensible parameters of the non-linear transfer functions for rotations and translations were obtained from preliminary experiments using the same task as for the main experiment. To facilitate larger rotations and to increase the sensitivity for smaller rotations with the trackballs of the GlobeFish and GlobeMouse devices, we implemented the non-isomorphic 3D rotational techniques suggested by Poupyrev et al. [14]. We used a non-linear transfer function of the type $y = a\ x^b$, in which x is the rotation angle in the quaternion basis, a is a normalization constant and b is the exponent. For rotations, exponents in the range of 1 to 5 were tested. Among the tested values, an exponent of 3 resulted in the best task performance, so it was chosen for the study. For the translations, a similar transfer function was used and an exponent of 1.8 was found to work best. For the isotonic trackball rotations, we used position control and for the elastic rotations and translations, we used rate control. For all axes, translation and rotation values of the devices were recorded at 48 Hz, which was also the frame rate of the graphics application.

Two tetrahedra of equal size formed the target and the cursor (Figure 6). Spines around the vertices served as an indication of the docking tolerance. The orientation of the tetrahedra was given by coloring the edges and vertices. Vertices changed color when the cursor was positioned within the docking tolerance. Stimuli were presented on a 22” monitor running at 96Hz using active stereo with shutter glasses. The target was always presented centrally 12 cm in front of the monitor. For the cursor, there were four starting positions, each of them having the same Euclidian distance to the target and similar rotation offsets.

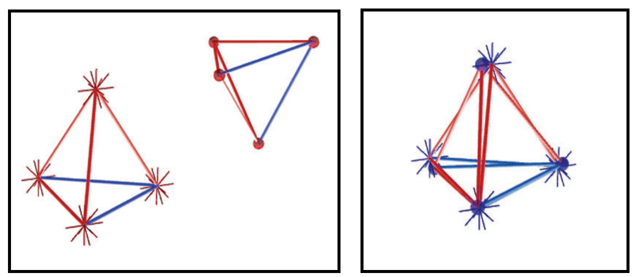

Figure 6: The 6-DOF docking task. The left image shows the target on the left side and the cursor on the right side. The cursor was controlled by the input device. The right image shows a successfully completed docking task. The spines around the vertices indicate the docking tolerance.

Design and Procedure

All participants performed the task with each of the four devices (small GlobeFish, large GlobeFish, GlobeMouse, SpaceMouse) during two consecutive days, two devices per day. The order of devices was balanced across participants using a Latin square design.

On the first day, length and width of the participants’ right hand were measured, and previous experience with computers and devices as well as handcrafting skills were assessed. The task and the first device were explained followed by three training trials. Then, a first block of twelve trials (three repetitions of four cursor positions in random order) was performed. A trial was started by a key-press and ended when all vertices were positioned within the docking tolerance for 0.8 sec. A practice session of five minutes was performed before the second, third, and fourth block. The design of all blocks was as described for the first one. After these four blocks, participants filled out a written questionnaire asking about ease of rotation, ease of translation, usability, and various device features, each on a 6-point scale. At the end of the second day, participants reported their most and least favoured device. In total, the experiment lasted about four hours per participant.

Results and Discussion

Task Completion Times

Mean task completion times (TCTs) are depicted in Figure 7 separately for three devices, namely the small GlobeFish, the GlobeMouse, and the SpaceMouse. The large GlobeFish produced rather long means (21.86 sec) compared to the other devices together with an extremely high amount of variability (standard deviation s=12.28 sec). This was due to some unintended input delivered by the large GlobeFish. The self-centering mechanism of the mechanical translation sensors of the device did not work smoothly. This resulted in unintended cursor movements. This deficit was already observed while conducting the experiment. Because of the experimental design, we continued to establish performances also for the large GlobeFish despite its obvious mechanical problems. However, the data for the large GlobeFish was not analyzed.

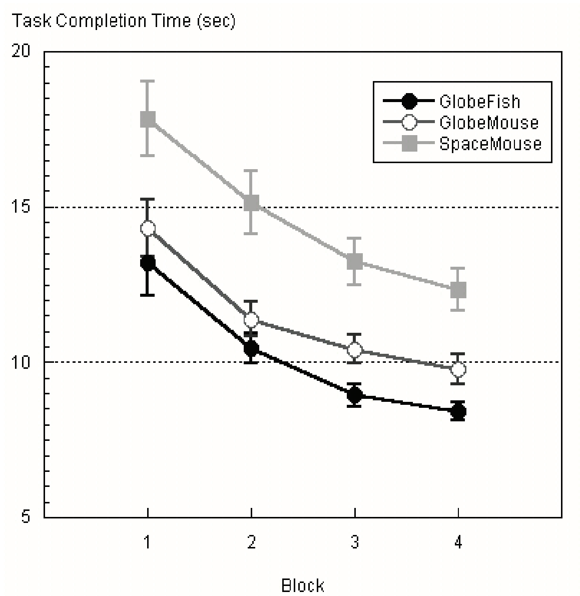

Figure 7: Mean task completion times and standard errors are depicted over four blocks separately for the small GlobeFish, the GlobeMouse, and the SpaceMouse.

TCTs for each block were entered in a 3 * 4 - analysis of variance for repeated measures with the within-factors device (small GlobeFish, GlobeMouse, SpaceMouse) and block (1, 2, 3, 4) as well as the between-factor order of devices. Effects were evaluated using the Greenhouse-Geisser correction. One participant produced mean TCTs twice as large as the maximal TCTs of all others with all devices. This data was discarded from analyses. Post-hoc comparisons were done using Newman-Keuls tests.

First of all, the order of devices did not produce a main effect ($F_{3,11}$=1.76, p=.21) nor did it interact with any other variable (interaction with device: $F_{6,22}$=2.13, p=.12, with block: $F_{9,33}$<1; with device times block: $F_{18,66}$=1.51, p=.20) indicating that the transfer from one device to another was comparable.

Performances for the three devices differed significantly ($F_{2,22}$=24.86, p<.001). Whereas with the small GlobeFish it took 10.25 sec (standard error se=.48) to dock the cursor, and with the GlobeMouse 11.47 sec (se=.53), with the SpaceMouse the longest TCTs were obtained (14.62 sec, se=.84). Post-hoc comparisons revealed that all devices differed significantly (all p<.01) from each other. In addition, performance improved over the four blocks ($F_{3,33}$=58.83, p<.001) from 15.11 sec (se=.81) in block 1 over 12.32 sec (se=.54) in block 2, 10.86 sec (se=.47) in block 3 to 10.17 sec (se=.39) in block 4. This decrease in TCTs did not differ between devices ($F_{6,66}$<1) suggesting that all three devices produced comparable improvements due to learning.

Effects on Rotation Movements

The advantage for the GlobeMouse and the small GlobeFish over the SpaceMouse still leaves open the question of the source of this superiority. One obvious assumption was that the isotonic position-based control of rotation is of advantage as suggested by [10]. This question was addressed by comparing the times of rotation and of translation movements for each device. If rotating movements are actually easier to perform with the new devices, then rotations should take less time for these devices.

TCTs were separated into times of no movement, times of rotations, and times of translations. The amount of time spent for rotation or for translation is depicted in Figure 8 (note that rotation and translation may occur simultaneously which may add to more than TCTs). As can be seen, shorter times for our new devices are especially pronounced for rotation. To control for the absolute differences in TCTs, fractions of rotation and translation were statistically compared. Whereas translations occurred about equally often for all devices (GlobeFish: 74.37%, GlobeMouse: 64.14%, SpaceMouse: 71.11%), control of rotation was less frequent for both of our new devices (GlobeFish: 25.75%, GlobeMouse: 19.20%) than for the SpaceMouse (55.06%; interaction between device * kinds of movements: $F_{2,14}$=115.64, p<.001). This confirms that the GlobeFish and the GlobeMouse both facilitate control of rotation for the users.

The interaction between the kinds of movements and blocks ($F_{3,13}$=11.89, p<.01) shows that whereas the fraction of rotations did not vary with blocks, the fraction of translations increased with increasing blocks. This learning

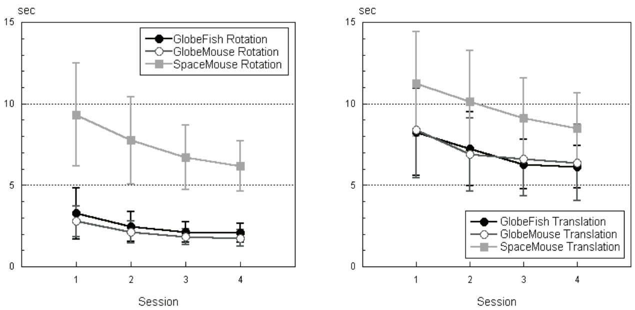

Figure 8: Time needed for rotation (left) and translation (right) in four blocks separately for the small GlobeFish, the GlobeMouse, and the SpaceMouse.

effect did not differ between devices, perhaps partly due to the large variability for rotations with the SpaceMouse. Nevertheless, Figure 8 shows that rotation took about 2 to 3 seconds with our new devices during sessions two to four, which is fast and hardly improvable.

Based on these results we believe that the superiority of our new devices is very likely due to their isotonic position control based rotation. Kim et al. [10] reported 30% to 40% faster rotations with their 3D trackball than with a SpaceMouse in a rotation only task. In our study, we can see even larger differences, which might be due to involuntary rotations occurring during intended translation phases and possibly careful use of the SpaceMouse to avoid these unintended couplings.

Subjective Ratings of Devices

After having performed four blocks of trials with one device, participants were asked about the ease of rotations and translations. Figure 9 shows the marginal effect for the rated ease of rotation ($F_{2,22}$)=2.75, p=.09) indicating that rotations with the GlobeFish and the GlobeMouse were judged as easier than with the SpaceMouse. Translations, however, were rated as significantly easier with our GlobeMouse than with the SpaceMouse and the GlobeFish ($F_{2,22}$=7.96, p<.05, see Figure 9). As problems for translation using the SpaceMouse, users reported mainly that they often failed in translating only and rotated simultaneously instead. For the GlobeFish, they objected to the large force it takes to translate. Since the GlobeFish employs a SpaceMouse controller in the left socket counterbalanced by a set of springs in the right socket, it requires twice the amount of force as the GlobeMouse device.

Ratings of manual motor fatigue differed between devices ($F_{2,22}$=13.37, p<.01). The GlobeMouse was rated with 5.5 (se=.18) best (6=no fatigue, 1=very strong fatigue) suggesting that re-grasping does not seem to be detrimental. For the GlobeFish, mean motor fatigue was 3.44 (se=.38), confirming the problems with the force necessary to control the device. Subjective motor fatigue for the SpaceMouse (3.82, se=.34) did not differ from that of the GlobeFish.

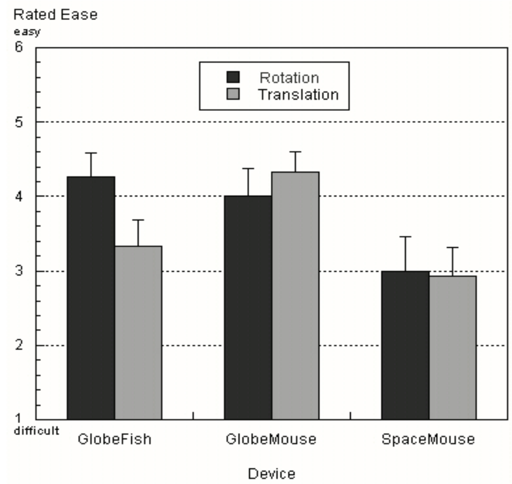

Figure 9: Ratings of ease of translation and ease of rotation for the GlobeFish, the GlobeMouse, and the SpaceMouse.

Other subjective data also provided clear advantages for the newly developed GlobeFish and GlobeMouse. For example, usability (from 1= extremely good to 6=extremely poor) for the GlobeFish was rated with 2.06 (se=.28) and for the GlobeMouse with 1.58 (se=.18) significantly better than ratings for the SpaceMouse (3.04, se=.31; $F_{2,22}$=9.62, p<.01). Also, the transformation of the hand movement to the movement of the cursor was judged to be better for the GlobeFish (1.92, se=.22) and the GlobeMouse (2.04, se=.33) than for the SpaceMouse (3.17, se=.43; $F_{2,22}$= 5.11, p<.05). Eight participants (53.3%) chose the GlobeFish, six (40%) the GlobeMouse, and one (6.7%) the SpaceMouse as their favorite device.

Times of no Activity

Times during which no activity was recorded for any DOF include the time it takes to switch the grip as well as times of cognitive processing. Mean fraction of no activity was 14.93% for the GlobeFish. For the SpaceMouse, 18.19% of no activity time was observed. This difference might be assumed to reflect differences in cognitive processing due to an increased difficulty for rotation with the SpaceMouse. Nevertheless, with 26.33% the GlobeMouse produced the highest amount of no activity. Since one obvious reason for that is the additional time required to change the grip, one might hypothesize that by shortening the distance between the trackball and the translation base the TCTs for the GlobeMouse can even be reduced further.

Discussion

In summary, both our new devices performed better than the SpaceMouse. One might argue that a comparison with a standard 2-DOF mouse is still missing. However, the 2-DOF mouse requires the usage of keyboard short cuts or widgets. As already mentioned, other studies [1,7] have already shown that these approaches are inferior to integrated control for 3D rotational and translational tasks. Moreover, our own preliminary tests confirm these results.

The standard 2-DOF mouse and keyboard short cuts cannot even compete with the SpaceMouse.

When comparing the GlobeFish with the GlobeMouse, several arguments in favor of both can be derived. First of all, docking was faster with the GlobeFish than with the GlobeMouse. This might be due to the additional time it takes to change the grip when switching between translation and rotation with the GlobeMouse. In addition, the GlobeFish was preferred by most users.

Nevertheless, the GlobeMouse also produced certain advantages. The fraction of translations was the smallest for the GlobeMouse. Moreover, translation with the GlobeMouse was regarded as the easiest. This might be attributed to the fact that the GlobeMouse provides a tactile spatial reference frame, thus facilitating finding the optimal grip position necessary to achieve certain movements. In addition, the GlobeMouse was rated as providing the best usability and producing the least manual motor fatigue. The higher motor fatigue evoked by the GlobeFish, however, might be reduced by reducing the required forces for translations.

CONCLUSIONS AND FUTURE WORK

We presented new 6-DOF desktop input devices which combine isotonic rotational input with elastic translational input. Although our devices were only prototypes, the results provide clear evidence that they are superior to the SpaceMouse in a docking task. This was shown in performances as well as in subjective ratings. The fraction of rotations as well as subjective ratings of their ease indicated that the advantage of the GlobeFish and the GlobeMouse can be primarily attributed to the facilitation of rotations. These results also suggest that a 3 DOF + 3 DOF design is better suited for docking tasks than an integrated 1 * 6 DOF-approach. This indicates further that the mental structure of this task is separated with respect to translations and rotations. Other tasks such as navigation or selection might evoke a different mental structure thus requiring a different separation or integration of the DOF.

Our GlobeFish and the GlobeMouse can also be used for 2D input in desktop applications. Users would have the choice of using the isotonic trackball or the elastic translations for 2D control, whatever seems most appropriate for the task. One could also apply this concept of redundant DOF to the 3D domain to go beyond six DOF in a single device, a possibility already inherent in the GlobeMouse.

We are going to build further prototypes of the devices to optimize our current design. Studies of differently sized trackballs as well as variations on the travel of the trackball and the required forces are necessary. A design which does not fully enclose the trackball around the equator provides more comfortable access to rotations around the vertical axis (Figure 10). A vertical orientation of the trackball's frame (Figure 11) would also be an option for a relaxed hand orientation, at the disadvantage of losing the visible representation of a coordinate system. Buttons are required for most applications. However, a particular challenge is to position them on our devices without interfering with the 6-DOF input. Attaching the trackball to a 3-DOF Phantom device or a small motion base would allow the simulation of different translational forces in addition to the possibility of providing force feedback.

Figure 10: A GlobeFish prototype providing comfortable access to the 3-DOF rotations.

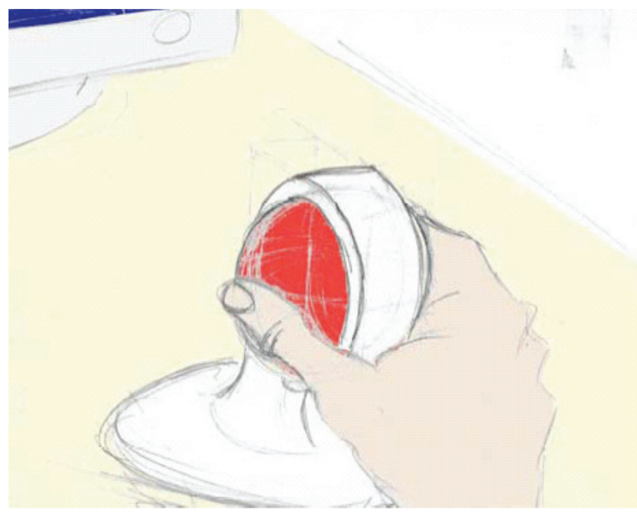

Figure 11: The GlobeFish with a vertical frame.

The GlobeFish and the GlobeMouse are new devices bearing the potential of becoming an alternative to commercially available 6-DOF solutions. Nevertheless, the unexplored design space for these types of devices is still large. For each DOF, we have the choice of using isotonic, elastic, or isometric input sensors. Some of the DOF could be integrated, others separated. 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, the remaining challenge is to find spatial arrangements of sensors which provide comfortable access to the six or more DOF in a single device.

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