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The DigiTracker, a Three Degrees of Freedom Pointing Device

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Abstract

For a variety of reasons, only a few computer devices allow to achieve pointing, tracking and selecting tasks in a precise, fast and intuitive way in 3D workspaces. This article presents the ergonomic and technical principles that have conditioned the proposal of a desktop input device called "DigiTracker". The user controls the position of a virtual object by grasping an isotonic end-effector between the thumb and the forefinger while his forearm is laying on the desk. This equivalent to an absolute three degrees of freedom mouse is especially suitable for closed virtual workspaces. The low technological cost of this solution could provide a really worth alternative to complex VR tracking systems. Possible applications are remote positioning tasks or CAD in simultaneous use with a device dedicated to rotations control .

Categories and Subject Descriptors (according to ACM CCS): H.5.2 [Information Interfaces and Presentation]: Input devices and strategies

1. Introduction

Technology advances have driven PC hardware capabilities up and prices down, thereby allowing fast developments and an already wide spread use of 3D software such as games, VRML web-based worlds, CAD and many others applications. The introduction of a third visual dimension on display has resulted in mediating the 2D shortcomings which essentially were the lack of realism and the impossibility to display a large amount of data simultaneously. With this revolution in computer graphics, one can wonder how the 2D mouse established as a traditional computer input devices and specifically designed for WIMP interfaces could be replaced by an equivalent device allowing the user to achieve pointing, tracking and selecting tasks on virtual 3D objects.

The motivation that led us to create a new input device comes from a 3D user interface for synchronous cooperative work called "SPIN-3D" (see Figure 1). Here, users remotely interact with each other via their respective clones in closed workspaces requiring two appropriated 3D input devices for pointing out and rotating 3D objects [DDS*99]. In situation of use, the human has to be able to focus on a closed workspace containing virtual objects and to forget the interaction techniques [KBS94]. Whereas two easy to use 3D devices that allow rotations of a virtual cursor or hand were available [CPCS03] [DPK85], tested pointing devices remained unsatisfactory since the use of two hands means that each hand must stay in the approximate vicinity of the area in which the work is carried out [DET90].

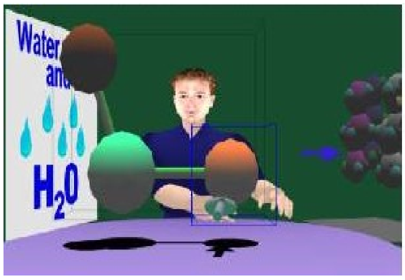

Figure 1: *A 3D interface for cooperative work : SPIN 3D.*

In this article, we first present a definition and classification of tracking devices. Then, we describe the ergonomic and technical consideration that have conditioned the design issues. Finally, we relate trials on example applications with underlining the contributions of the new device and its limitations.

2. Tracking devices definition and classification

2.1. Tracker definition

Solids or 3D objects have 6 degrees of freedom (dof) : their position coordinates (x, y, z) and their angular orientation (pitch, yaw and roll). A tracker is a communication device which supports these parameters or a subset by getting a user's body part state. Also, a tracker is a sensor which captures position and/or angular displacements from the user's modulation gesture in order to provide proportional effects on the object.

2.2. Position control

According to Shumin Zhaï [Zha95], isotonic devices provide better performance for position control than isometric ones which are more convenient for rate control. In the first case, the user displaces a sensor whith equal dynamics between each degree of freedom and zero or constant low resistive forces. In the second case, he applies forces or torques on a high resistive sensor which maps them into a proportional displacement on the screen. Since position trackers map positions directly and proportionally, their technology has to allow a great freedom of movement in order not to disturb the user's gesture, therefore being typically isotonic.

2.3. Absolute and relative control modes

Trackers can be either absolute or relative depending on the physical and virtual workspaces boundaries. In absolute mode, the position of the user's limb or of the device's free moving point corresponds to a unique position of the virtual pointer and consequently, the virtual workspace dimensions have to be adapted to the user's operating range. In relative mode, the sensor sends position variations to the processing unit. A clutch allows the user to re-center the physical position without affecting the virtual one. This mode allows him to interact in workspaces with unrestricted dimensions.

2.4. Attachement to the user

Trackers can be divided into two categories : body and ground-based devices. The first ones are permanently linked to a user's limb. It is the case of sensors that remain glued to a finger or a wrist and remotely send informations to a processing unit. For example, the Flock of Birds® by Ascension Technology consists in an emission source and many receivers attached to the human. The second ones allow to extract positions of a free moving point defined in relationship with the grasping of a control device. The PHANToM® from Sensable technologies outputs the 6 dof coordinates of a stylus tip grasped in the user's hand and mechanically linked to the desk. Desktop tracking devices belong to this category.

2.5. Desktop tracking techniques

Tracking technologies used in VR (Virtual Reality) applications are mainly mechanical, optical, ultrasonic, electromagnetic and inertial [DM95]. The most widespread is the magnetic one [Kin99] which is mainly used in motion capture and allows to measure position and orientation of a mobile mark compared to a fixed reference one.

These techniques have been essentially studied as body-based. Apart from the mechanical one which can be ground-based and so adapted to an office use, the others ones are incompatible with a simultaneous work with an other input device or with repeated work interruptions. Moreover, a tracker requires a low latency, a high update rate and a high accuracy and it is noteworthy that this last parameter becomes very decisive in small workspaces. If these qualities may be found in a mechanical arm [KM92], a user centred study, described thereafter is necessary to avoid poor ergonomic features and to keep the user's freedom of movement.

3. Ergonomic design

In situation of interaction with a 3 dof workspace, the user's attention is mainly held by the visual clues. The device's transparency is therefore a crucial design requirement to avoid disturbances caused by the use of complex interaction techniques.

3.1. Natural gesture

Human exteroceptive pre-existing abilities (e.g. the limbs positions awareness) for pointing, grabbing and moving objects in space are pre-existing skills people have developed through a lifetime of interaction with the physical world [IU97]. In order to avoid user tiredness, to give realism and to considerably reduce the device learning time, it is necessary to take advantage of a natural interaction metaphor fully compatible with an office use. Consequently, clutching and declutching actions encountered in a relative control mode should be avoided in order to minimize the cognitive load of the user. Moreover, the inner structure of the device must be dissimulated by a shell in order not to distract him.

3.2. Accuracy and working posture

Many studies [LCF76] [ZMB96] [CMR91] comparing the speed of the user movements depending on the complexity of the pointing tasks have highlighted that the more he utilizes the end of his upper limbs, the more he increases his efficiency in comfort situation. A later study has moderated these results by claiming that only the thumb and index fingers working together surpass all the other limbs segments [BM97]. Wrist performances are slightly below showing a quasi similar accuracy but a greater response time . All of these trials show that dynamic precision grasps exploit the user dexterity, and consequently, a prismatic one [CH90] is well appropriated to translate a free moving point along 3 dimensions. Among the various possible finger configurations, the pulp-2 pinch grasp (Figure 2) is the most suitable for small areas and high precision activities such as threading a needle.

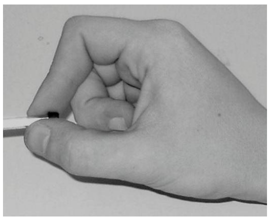

Figure 2: *A pulp-2 pinch grasp.*

The posture adopted when performing a computer task is a particular orientation of the body and its parts in order to establish the connection with the workspace. The Digitracker is intended for office use, therefore it must be designed specifically for this context. In order to avoid tiredness and to gain efficiency with constraining a part of the arm kinesthetic chain, it is necessary to keep the arm along the body and to lay down the forearm on the desktop. Its flexion angle with the arm is static and is about of 90-120°. A neutral hand palm orientation existing when people are holding hands has to be favoured with the idea of avoiding static forearm pronation and wrist extensions encountered with the traditional 2D mouse.

3.3. Physical workspace

Contrary to the touch sensitive screens that allow to point out icons directly on a flat display area, the use of a 3 dof input device prevents strictly direct actions on a classical screen. A translation offset between the virtual and physical references marks is indeed necessary introduced since the input and screen spaces cannot be superimposed.

In [BGBG95], a taxonomy of classifying according to the directness of transformation between spaces gives transparency guidelines that are isomorphism and a control display gain (CD-gain) equal to one. The first recommandation means that the virtual space axes have the same orientations and directions as the physical ones. The second claims that both virtual and physical workspaces must have the same dimensions. If previous studies [Bur00] have underlined the need to extend input devices to large virtual volume areas for body-based devices, others [FV02] have concluded that the workspaces differences between ground-based devices and a projection screen are relatively unimportant. The literature is in fact inconclusive on the effect of the C-D gain on 2 dof or 3 dof selection tasks performances with absolute devices: Arnaut and Greenstein [AG86] advised a C-D gain equal to one for a touch tablet whereas Buck [Buc80] claimed that varying the C-D gain had no effect on performance time since the target width must be taken into account. In our case, the display space would be oversized compared to the one of the index and thumb while they work in synergy. A virtual workspace could be easily adjusted to the physical one by reducing the dimensions of the application but like Balakrishnan and Mackenzie [BM97], we prefer a close to six C-D gain for fingers in order to keep the same visual stimuli on usual applications. Consequently, we delimit the borders according to the motor skills of the user.

The literature provides very few information about the 2-pinch grasp 3 dof modeling since this grasp allows mainly planar motions. However, a study [GFTC00] about the mapping from a human hand 2-pinch grasp to a robotic 2 dof one shows the workarea of a virtual sphere held between the thumb and index under experimental conditions . The reachable surface has roughly been approximated to be 70*50mm along the width and the depth of the workspace and the short movement amplitudes along the third dimension lead us to carry out experiments with users in order to design an isotonic workspace.

A first plexiglas® prototype (Figure 2) has been built in order to empirically define the workspace of a midpoint beetween fingertips when the user holds a 6 mm diameter cylinder. An experiment carried out toward 10 students

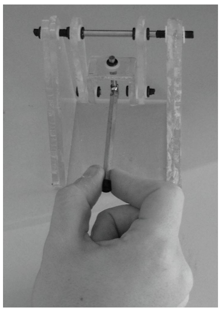

Figure 3: *Plexiglas® prototype.*

(7 males and 3 females) has allowed us to measure positions of the midpoint with a ruler. The subjects were asked to reach the vertices of a rectangular parallelepiped without moving the wrist. The parallepiped sizes are the average values between the two groups and are roughly: 45 mm along the width of the screen, only 15 mm along the height and 30mm along the depth. These trials have highlited that wrist flexions, extensions and abductions are necessary to compensate the forearm constraints and therefore to work with a good comfort level. Under these conditions, the accepted workspace size with the sample group assent is 60 mm in width, 50 mm in height and 30mm in depth. The final workspace dimensions are 60×45×30mm (Figure 5) in order to provide isotonic displacements in a display workspace size of 1024×768×512 positions. A 17” screen diagonal

leads us to a control-display gain of 5.73. The volume center is located at 55mm above the desk plane.

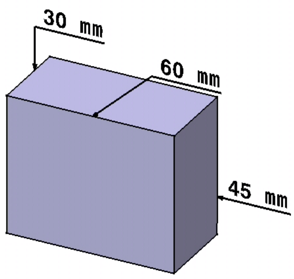

Figure 4: *Workspace dimensions.*

4. Technical features

Our device is a 3 dof ground-based tracker that transmits the absolute positions of a serial linkage tip to the computer when the user holds, moves and operates a selection switch.

4.1. Linkage kinematics

The second Digitracker prototype [MPC03] is constituted by a base, an open serial linkage of rigid bodies connected by moveable joints and a gripper used as an end effector.

The base of the Digitracker is a stable platform that supports the mechanical arm and prevents it from sliding on the desk. Electronics may be contained inside.

As discribed in Fig. 5, the mechanical arm is a 3-bar linkage (L1, L2, L3) with three revolute joints (R1, R2, R3). The R1 and R2 pivot axes are parallel and the R3 is orthogonal to the others. Several linkage possibilities were available when

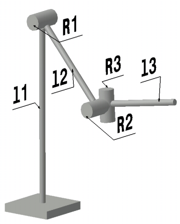

Figure 5: *Linkage kinematics.*

we were looking for the most isotonic and this one seemed to us to be the best since R2 and R3 pivots make a ball and socket joint comparable with that of a computer joystick. This type of joint allows free movements on a sphere, in any angular direction, within the limits of the socket. The third revolute joint has been preferred to a sliding one for friction control purposes. Trials on a spherical configuration mixing the two types have indeed highlighted that displacement directions are influenced by the lack of a snug fit between the sliding surfaces.

The linkage tip coordinates in the physical workspace are computed using the following transformation equations:
$Xpos = L3 \times \sin R3$
$Ypos = L2 \times (1 - \cos R1) - L3 \times \sin(R1+R2) \times \cos R3$
$Zpos = L3 \times (\cos(R1+R2) \times \cos R3 - 1) - L2 \times \sin R1$

Inverse kinematics have been calculated for extreme workspace positions with in order to proportion the bars lengths. When the L2 pendulum swings around the R1 axis, it may move away from its balance position and therefore, the system potential energy increases with the L2 and L3 bars lengths and with the L2-R2-R3-L3 linkage mass. Consequently, it is necessary to minimize these quantities in order to avoid great apparent mass variations on the gripper when the user holds and manipulates it. The bars dimensions are L1=108mm, L2=58mm and L3=80mm. The angular ranges are R1=55°, R2=60° and R3=89°.

4.2. Position preservation

The end effector needs to remain in position when released in order to match the device with work interruptions and to prevent fortuitous fingers slippage. For this purpose, we voluntary introduce very low controlled frictions using strict mechanical tolerances. In this way, the lightweight parts are kept in out of balance positions in the physical workspace range without brakes, as shown in Figure 6.

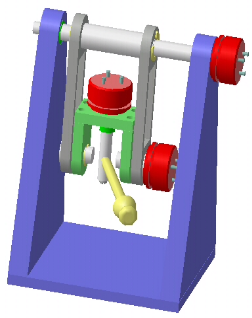

Figure 6: *Digitracker design.*

4.3. Data acquisition

Relative motions between rigid links are sensed directly on each axis by a precision potentiometer in order to read absolute positions in the physical workspace, to ensure no loss of information in time and no calibration.

Minimums of angular position differences for motions between adjacent pixels computed with equations solutions of inverse kinematics throughout the physical workspace have provided the resolution requirements. The results have shown that a physical resolution of $1024 \times 768 \times 512$ positions results in a theorical maximal angular resolution of 20 bits within the operating range of the sensor on the R1 and R2 axes. However, we permit a very little workspace distortion and choose a 14 bits resolution to keep distance errors lower than half a pixel.

Our device draws power directly from the USB bus and three 16 bits Sigma-Delta Analog to Digital Converters get low levels input signals (5V) and send it to a multiplexed parallel port of a USB compliant microcontroller. The three analog channels and a digital one built for a switch are read at a sampling frequency of 50Hz for each channel. The LCD screen technology causes a 30 ms display latency and the USB communications last 10ms per cycle.

4.4. Gripper and selection button

The gripper has a feeding bottle teat form and offers several crucial functions. First, since when there are less than three fingers in contact, the object orientation is not fully determined [Tur01], a spherical precision gripper held with weak forces provides an imaginary ball and socket joint between the L3 rod and the two fingers linkages. In this way, the user manipulates a free moving sphere without being constrained by L3 bar orientations. Then, the curvatures in the middle of the gripper increase the grasp stability when L2 is in an out of balance position. Finally, a low stroke switch fits inside and provides a discrete input when pressed laterally according to the grasp.

5. Preliminary results

Preliminary trials have been performed in demonstration applications and within this framework, the users were asked to achieve pointing, tracking and selecting tasks. Participants first fit their posture to the workstation by reaching the virtual workspace boundaries in order to find the most natural position and to check the even feel sensation of the device resistance throughout the workspace. While using the Digitracker, they continue to focus on the screen and their performance essentially seems to be depending on user's fingers dexterity. The Digitracker requires no learning time since subjects aren't required to mentally break down the 3D task into 2+1D parts.

The Digitracker is intrinsically robust since it's only sensitive to the negligible errors coming from the mechanical tolerances and the potentiometers. Its responses are fast and accurate. It is compatible with work interruption as the linkage tip is held in position.

By example, as illustrated in Figure 7, The Digitracker and a custom-built Visual C++/OpenGL application allow the user to quickly point and switch on colored lamplights in a virtual 3 dof room.

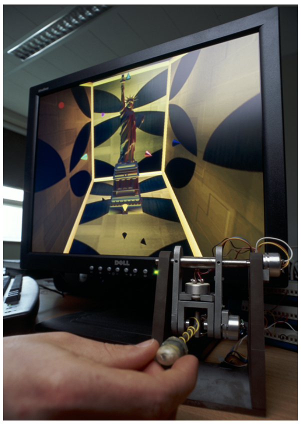

Figure 7: *Colored Lamplights switch on application ©INRIA/Photo J. Wallace*

6. Conclusion and future work

With the view of clearly setting our proposal, we have first presented a definition and classification of tracking devices. We have seen that a tracker may be especially intended for isotonic 3 dof position control of virtual objects in closed workspaces. We have put forward that a ground-based mechanical tracker is the most suitable solution for an office use since there is no need to equip the user and it offers the best metrological properties under ergonomic conditions. Then, a user centred ergonomic study has given transparency and accuracy guidelines according to human 3D perception and fingertips. Finally, ve have presented the main mechanical and electronical features of a 3 dof mouse-equivalent usable in closed workspaces.

However, the high CD-gain increases hand tremor noise and deviations resulting of selection actions on small objects. A filtering technique of involuntary tiny displacements has been successfully tested but one can wonder if the use of fingers doesn't result in a too much expressive input device.

For the future works, we first plan to investigate software interaction metaphors which would allow to go against little displacements and selection action shortcomings. A plastic shell will then hide all mechanisms and particularly the pendulum for transparency purpose. We finally expect to use very small TWUM (Travelling Wave Ultrasonic Motors) directly mounted on each axis to render force feedback on each dof and provide a real isotonic workspace by compensating the inertia of mechanical parts.

7. Acknowledgements

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