The Roly-Poly Mouse: Designing a Rolling Input Device Unifying 2D and 3D Interaction

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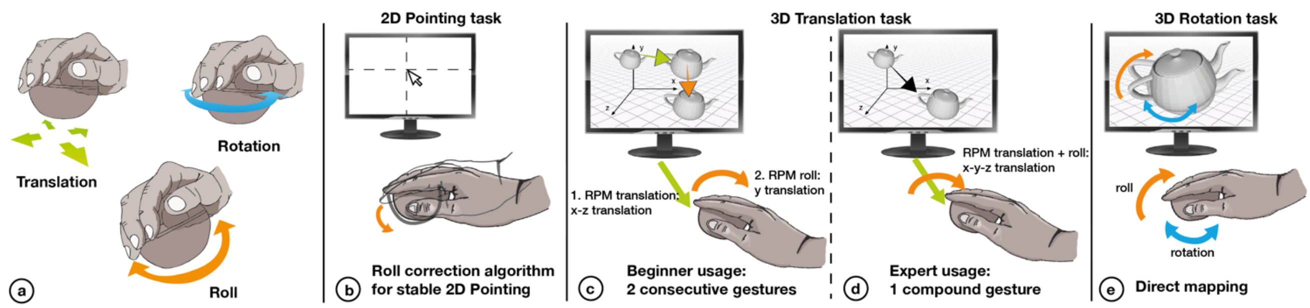

Figure 1.a) The Roly-Poly Mouse (RPM) gestures. RPM can be used for b) 2D pointing; c-d) 3D translation by combining RPM translation and roll; e) and 3D rotation by combining RPM roll and rotation.

ABSTRACT

We present the design and evaluation of the Roly-Poly Mouse (RPM), a rolling input device that combines the advantages of the mouse (position displacement) and of 3D devices (roll and rotation) to unify 2D and 3D interaction. Our first study explores RPM gesture amplitude and stability for different upper shapes (Hemispherical, Convex) and hand postures. 8 roll directions can be performed precisely and their amplitude is larger on Hemispherical RPM. As minor rolls affect translation, we propose a roll correction algorithm to support stable 2D pointing with RPM. We propose the use of compound gestures for 3D pointing and docking, and evaluate them against a commercial 3D device, the SpaceMouse. Our studies reveal that RPM performs 31% faster than the SpaceMouse for 3D pointing and equivalently for 3D rotation. Finally, we present a proof-of-concept integrated RPM prototype along with discussion on the various technical challenges to overcome to build a final integrated version of RPM.

Author Keywords

Input Device; 2D Pointing; 3D Interaction.

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ACM Classification Keywords

H.5.2. Information interfaces and presentation: Interaction

INTRODUCTION

3D applications are more popular than ever with the advent of easy-to-use 3D editors (SketchUp), 3D printing and web 3D engines (Unity Web Player, Flash 3D). Affordable multi-degrees-of-freedom (DOF) devices, such as the SpaceMouse (with over a million units sold [27]), contribute to this development. However these devices are not well suited for 2D pointing in WIMP interfaces [11] (3D editor menus, web browser GUI or when switching to 2D applications). They usually work in rate control mode, less convenient for 2D pointing [36]; DOF are difficult to operate independently [11]; and some devices are bulky, or tiresome to use such as the Phantom [24]. Therefore users need to switch between the mouse and the 3D device, which is tedious and inefficient [11]. Relying only on the mouse for 3D tasks is less effective [1,9]. An all-in-one device would therefore remove device-switching costs (Homing in KLM [6]) and improve the workflow of the users of 3D applications in 2D WIMP environments.

Previous works have augmented a regular 2D mouse with additional DOF [1,13] by adding rounded edges to enable rocking gestures. These devices are limited by their initial mouse-like form factor, with a flat surface to assure the device's stability. The different DOF, i.e. mouse translation and rocking, are physically separated and the flat spot at the base of these devices physically drives the user to control only two degrees of freedom simultaneously. Besides, the rocking amplitude is limited to a rather small curved surface, thus diminishing the range of input values. In our approach, rather than providing a mouse with additional DOF, we choose to provide a rounded shape, intrinsically offering 3 DOF rotations, with capabilities for handling 2D translations.

In this paper we present the design of a rolling input device offering up to 6 DOF: the Roly-Poly Mouse (RPM). This device mimics the well-known roly-poly toy: the base of the device is hemispherical and can be rolled (2DOF), rotated (1DOF) and translated (up to 3DOF) in any direction (Figure 1).The key benefits of RPM make it a good candidate for an all-in-one device: RPM is free-moving as a mouse; has a large curved surface for rolling; and allows simultaneous and coordinated gestures to be performed by combining roll, rotation and translation. The design and usage of a symmetrical device with no stability constraint raises a number of challenges that we address in this paper: we study amplitude and precision along the different DOF; we propose a roll correction algorithm to support stable 2D pointing; and we design compound gestures for efficient 3D translation and rotation. We evaluate RPM against the SpaceMouse for 3D interaction, and results confirm that RPM is an efficient 3D device.

We build a proof-of-concept integrated prototype with a ‘ring’ button accessible on any device orientation and a 6DOF magnetic sensor. Using this prototype, we explore some usage scenarios that illustrate that RPM is not only interesting to unify 2D and 3D interaction, but also to extend several types of 2D applications by adding gestural control or commands.

Our contributions are 1) the design of a novel rolling input device through the experimental exploration of several design factors, 2) a novel roll-correction algorithm to support stable 2D pointing, 3) the design of a compound gesture for 3D interaction and a comparison with the SpaceMouse, and 4) a proof-of-concept wireless prototype along with usage scenarios and a discussion on technical challenges to build a final integrated version of RPM.

RELATED WORK

Mouse with multiple DOF

Prior works have augmented the regular mouse with additional DOF. Some of them added one DOF using two mouse sensors to support yawing [18,23] or a pressure sensor to control multiple levels of discrete selection modes [8, 15].These devices are however limited to 3 DOF.

Other mouse augmentations using 2 or 3 additional DOF have been proposed to allow 3D manipulations [1,13]. Rockin’Mouse [1] is a seminal input device with the shape of a regular mouse but with rounded bottom allowing the device to be tilted and thus offering two additional DOF. VideoMouse [13] is a similar device allowing for two more DOF (z-axis rotation and translation) by using a camera. These two planar multi-DOF devices derive from the mouse’s form factor: they add a rounded border to the bottom but keep the flat surface on the base to preserve device stability. One limitation of this design principle is that the narrow rounded surface restricts tilting degrees (+/-20° for the VideoMouse). Moreover even if Rockin’Mouse and VideoMouse allowed for partial compound gestures, these were limited by their form factor: the flat spot at the base of these devices physically drives the user to control only two degrees of freedom simultaneously. Studies with the Rockin’Mouse on a 3D task revealed that movements involving both planar and tilting movements occurred during the ballistic phase of the trial, while the final closed-loop phase involved one dimension at a time. Our device design is intended to increase the use of compound gestures thanks to its large hemispherical bottom that enables extended rolling and facilitates 4D gestures such as roll + translation.

The DesktopBat [28], a 5 DOF mouse, is based on the opposite approach: attaching a dome on top of a mouse, rather than below. The dome acts as an isometric input. No evaluation of this device in comparison with others has been reported so its key benefits are difficult to assess. The SpaceMouse is a 6DOF device [27] that requires dexterity as DOF are difficult to perform separately [9]: used with the non-dominant hand it is less efficient than regular mouse for 3D interaction [3]; however with the dominant hand, it has been reported to outperform the mouse [9].

Other techniques for 2D and 3D interaction

With the advent of multitouch surfaces, touch-based solutions for interacting with 3D environments have been proposed [10,12,20]. StickyTools [12] is a full 6DOF technique for rotation and translation of 3D objects. DS3 [20] is another technique based on the separation of translation and rotation that proved to be faster than StickyTools [20]. However, touch-based solutions are slower than the mouse or dedicated devices for 6D docking tasks [10]. Mid-air gestures have also been used to interact with 3D environments [24,34]. AirMouse [24] is a technique for 3D pointing in mid-air with a similar performance to that of 3D devices. 6D Hands [33] is a hand tracking system that supports bi-manual gestures for 3D manipulation. However, mid-air gestures induce fatigue and are not well suited for long interactions [24].

Round input devices

Our work is inspired by previous research on round devices [9,31,36,37]. The FingerBall (or FBall) [36] is a free-moving (isotonic) spherical device that can be held and moved in mid-air. The spherical form factor was intended to improve “precision grasp”, i.e. using one’s dexterity. The device showed better performance than a glove for a 6DOF docking task [37]. PALLA is a similar wireless device used to explore interaction with video games [31]. Globefish and GlobeMouse [9] are two 6DOF devices based on combining isotonic rotation with isometric translation. These devices perform well in rotation but, as with isometric devices, not in translation.

THE ROLY-POLY MOUSE (RPM)

The RPM is based on the form factor of the well-known roly-poly toy (Figure 2). The bottom is hemispherical, contains weight and its center of mass is low. When released, the device returns to its initial upright position after an inertial roll movement.

Gestures: translation, roll and rotation

The device offers up to 6 DOF with three types of simple gesture (Figure 1): translation (3 DOF), roll (2 DOF: pitch and roll) and rotation (1 DOF: yaw). In the context of desktop usage, we don't consider the z-axis translation due to fatigue: our studies explore the use of a 5 DOF RPM.

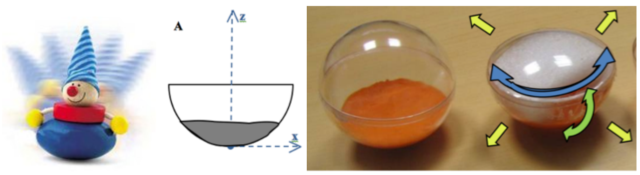

Figure 2. The roly-poly toy (a) has a low center of mass (b). Two RPM upper shapes: hemispherical and convex (c)

Key benefits

This form factor presents several key benefits that make it interesting for building an input device. As the device is **free-moving** in the x-y plane it can be used like an isotonic device such as the mouse [5]. The device contact with the surface is minimal, thus minimizing displacement friction. At the same time the device rolls and auto-repositions itself when released, **similar to an isometric device** [5]. The hemispherical bottom offers a large curved surface allowing for a wide range of possible input values. The device is symmetrical along its rotation axis (z) and thus can be used in any orientation. The three simple gestures (translation, rolling and rotation) can be combined to create **compound gestures**. For instance, effective 3D pointing with RPM is based on a compound gesture: translation + roll (Figure 1).

To sum up, this form factor combines characteristics from isotonic and isometric devices, making it a good candidate for an **all-in-one device** (Table 1 extends table in [13]). A 5 DOF device with such properties can be "very appealing to users who are reluctant to change their ways" [18].

Table 1. Comparison of sensed DOF for several multi-DOF mice (*Tz can be sensed by RPM but is not used).

Iput DOF	Regular Mouse		Rockin' Mouse [1]		Video Mouse[13]		Space Mouse [27]		Roly-poly Mouse	
	Sensed	Rate/Pos	Sensed	Rate/ Position	Sensed	Rate/ Position	sensed	Rate/Pos	Sensed	Rate/ Position
Tx	✓	p	✓	P	✓	p	✓	r	✓	p
Ty	✓	p	✓	P	✓	p	✓	r	✓	p
Tz	×		×		✓	p	✓	r	✓	p*
Rx	×		✓	r,p	✓	r,p	✓	r	✓	r,p
Ry	×		✓	r,p	✓	r,p	✓	r	✓	r,p
Rz	×		×		✓	r	✓	r	✓	r,p
T+R	×		×		×		✓	r	✓	r,p

DEVICE DESIGN FACTORS

As a first step in the design process of RPM, we identify and analyze the various factors that affect its usage.

Radius dimension

The size of RPM is based on the average size of a regular mouse (approx. 12x6cm). We carried out informal tests with three different diameter dimensions: 6, 8 and 10 cm. The 8 cm version was the easiest to handle and translate so all our RPM prototypes are based on this dimension.

Selection mechanism

The RPM cannot hold regular front buttons that would be difficult to reach when the device rotates. Two always-available solutions are to use a 'ring' button around the device (as the one in our working prototype) or a capacitive surface. In our studies we focus on RPM gestures and shape and don't evaluate these alternatives, left for future work.

Upper shape

We considered different shapes for the upper half of the hemisphere; hereafter, they are referred to as "upper shapes". Focusing on a symmetrical form that a hand would comfortably hold, we opted for a hemisphere and varied its degree of curvature and direction (in and out). In our preliminary study we initially consider three upper shapes: hemispherical, convex (curved out) and concave (curved in).

Hand grip posture

Previous psychological and physiological studies on the grasp of tangible objects show that the type of grasp (number and position of fingers) depends on the object shape as well as on the goal [22]. Grasp postures have also been previously used as an input modality [29]. Consequently, in our preliminary study we identify the most frequently adopted hand postures and explore them in subsequent studies to evaluate their impact on RPM gesture amplitude.

Gesture amplitude

Each one of the three gestures (translation, roll and rotation) has different amplitudes. The RPM is a wireless device and thus its movement in the x-y plane is unlimited. Concerning the roll and the rotation, their amplitudes are theoretically +90/-90° for roll and unlimited for rotation. However the hand posture and biomechanical limitations of the joints involved, such as the wrist, will restrain this theoretical amplitude [19,26]. By considering different hand postures in our first study, we collect the possible range of values for each type of gesture.

DOF Integration and Separation

The different DOF of the RPM are physically integrated: when performing a displacement, there will be some rolling; when rolling or rotating, the device's center of mass probably translates. To allow for a proper separation of the DOF of the device [14], we need to know how each DOF affects the others. We study this question in the first study of the paper.

Stability: Roll correction for 2D pointing

Due to the rounded shape of the device, we noticed unintended roll when translations are done. This poses a problem: when the device rolls, the center of the device moves and thus the mouse pointer is translated (Figure 3). Note that this problem is inherent to the device and not to the tracking technique: whether we consider the center of the device or the contact point with the surface, the problem exists.

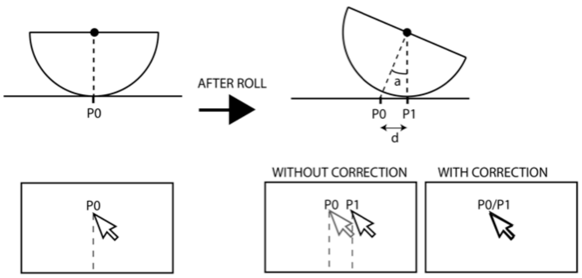

Figure 3. 2D pointing problem with a rolling device.

To solve this problem, we implemented a “roll correction” algorithm. This algorithm consists in calculating the position P0, which represents the device position upright, when the device is rolled into a position P1 (Figure 3). To calculate P0, we use the current position of the device P1, the roll and pitch angles a and p, and device radius R as follows:

$$P0.x = P1.x - \pi R * (\sin(a) + \cos(b))$$

$$P0.y = P1.y - \pi R * (\cos(a) + \sin(b))$$

In our implementation, when using the RPM as a mouse, we apply the algorithm for each frame to correct the roll deviation. We then calculate the displacement and apply the regular transfer function [7] to define the pointer position.

PRELIMINARY STUDY: UPPER SHAPES AND HAND POSTURES

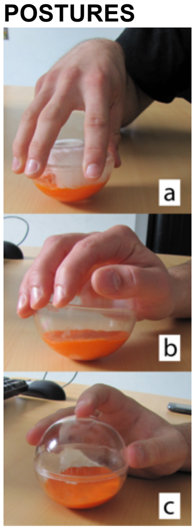

Figure 4. Most frequent hand postures.

The goal of this preliminary study was to collect most frequently used hand postures for each RPM gesture and user preference on the three considered RPM upper shapes.

Study Description

We studied 3 shapes (Concave, Convex and Hemispherical) and asked participants, for each shape, to hold the device with the dominant hand in four ways to perform four gestures: translation, roll, rotation and a compound gesture (in contact with the table). No interactive feedback was provided to participants and RPM was not tracked.

We recruited 12 participants (2 females) aged 24.8 years on average (SD=1.8). Two had previous experience with multiple DOF devices. We took 144 pictures corresponding to each hand posture (3 shapes x 4 gestures x 12 participants). We finally asked participants to order device shapes by preference. Each session lasted about 30 min.

Results

Over the 12 participants, 7 preferred Convex upper-shape, 4 Hemispherical and only 1 Concave. The Concave version of RPM was perceived to be difficult to hold and displace. In consequence we chose to remove it from the rest of our studies. Concerning the hand postures, we identified different recurrent patterns among which three were the most frequently adopted: Squeeze (Figure 4-a), Lay (Figure 4-b), and Touch (Figure 4-c). The following studies involve these three postures.

EXPERIMENTAL RPM TRACKING SETUP

In our following studies, we used the experimental tracking setup detailed below.

Tracking system

To track the translation, rotation and roll of the device we used infrared optical markers tracked by 12 OptiTrack cameras (1mm precision).The system senses the position (x, y, z) and orientation (yaw, pitch, roll) of RPM at 100Hz.

Prototype

The two RPM were weighted to be stable at rest (80gr each). Markers were placed on a support (Figure 5) to allow the cameras detect the device without impeding the user’s ability to grab the device with the three selected hand postures. Informal tests had also confirmed that the marker did not limit the amplitude of comfortable rolls: the maximum possible roll of RPM given these physical markers was 70° in the marker support directions. Our tracking setup did not register contact with the underneath surface, thus we did not use clutching in our experiments.

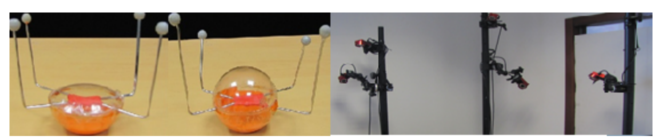

Figure 5. Experimental tracking setup.

STUDY 1: GESTURES STABILITY AND AMPLITUDE

We explore RPM gestures’ stability and maximum comfortable amplitude for each upper shape, considering various hand postures

Study Description

Task and instructions

Based on the preliminary study, we decided to study gestures stability and amplitude with two upper shapes (Convex and Hemispherical) and three hand postures (Squeeze, Lay, and Touch). We chose to control hand postures to avoid any confounding effect on the results as the user’s grip can have an important impact on the gesture amplitude. The task consisted in performing translations and rolls in 8 different directions and rotations in the two possible directions. We included two different distances (12 and 24 cm) for the translation task to study its effect on RPM stability. All distances and directions were drawn on the experimentation surface with circles and lines respectively (Figure 6). We asked participants to perform translations in a comfortable way from the center to the edge of the circle and back again to the center. Concerning rolls and rotation, we asked them to perform the maximum comfortable gesture. We used the tracking setup detailed in the previous section.

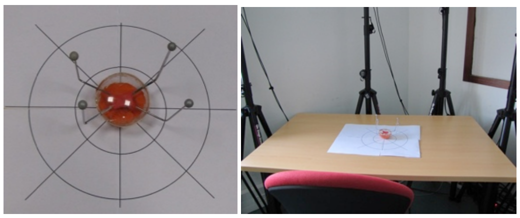

Figure 6. Study setup: distances and directions were drawn on the surface.

Participants
We recruited 12 participants (1 female) aged 25.7 years on average (SD=3.8). One had previous experience with multi-DOF devices and eleven took part in the pre-study session.

Design and procedure
The study follows a 2x3x4 within-subject design with Upper shape (Convex or Hemispherical), Hand posture (Squeeze, Touch or Lay) and Gesture (Short Translation, Long Translation, Rotation and Roll) as factors. We counterbalanced Upper shape and Hand posture. The study is made up of 6 blocks (each block is a combination of one Upper shape and one Hand Posture). Each block consists of 8 short translations, 8 long translations, 8 rolls and 2 rotations ordered randomly. After each trial, the device is placed in its initial position on the table.

Collected data and statistical analysis
We collected 2 devices x 3 hand postures x (16 translations + 8 rolls + 2 rotations) x 12 subjects = 1872 gestures. After each block we measured fatigue with a 6-20 Borg scale [4]. We used a Shapiro-Wilk test to determine the normality of the collected data. If the data was normal or could be normalized, we used a Univariate ANOVA test. If not, we used a Friedman test to compare more than 2 conditions and Wilcoxon tests otherwise. When we performed more than one statistical test on a particular set of data, we used the Bonferroni correction.

Results

Gestures amplitude
Rotation: We report the rotation amplitude for each direction (left and right), Hand posture and device Upper shape. A Wilcoxon test reveals no significant effect of the device upper shape on the rotation amplitude (Z=-0.98, p=0.33), thus we report mean values considering both upper shapes. A Wilcoxon test confirms a difference between left and right rotations (Z=-3.13, p=0.0017): left rotations are on average larger than right rotations (57° vs. 48°) (Figure 7-a). Results on Hand posture indicate that Squeeze allows for a larger average rotation than Touch or Lay (66° vs. 45° and 48°; $\chi^2(2)=24$, p<.001).

Roll: We report results on rolling amplitude (i.e. maximum degrees rolled in a given direction). An ANOVA test establishes a significant difference between RPM upper shapes ($F_{1,528}=34.319$, p<.001). The maximum average rolling amplitude is significantly higher with the Hemispherical RPM (39°) than with the Convex RPM (37°). Rolling amplitudes range from 27° to almost 60° depending on roll direction and hand posture (Figure 7-b,c).

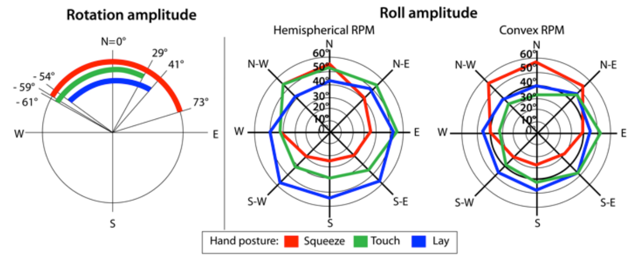

Figure 7. a) Rotation amplitude in degrees for each hand posture; b) rolling amplitude for the Hemispherical version and c) for the Convex version.

Gesture stability
Roll: Results on roll stability, i.e. deviation from the rolling direction, reveal no significant effect of the RPM Upper shape ($F_{7,528}=2.68$ p=0.09). Overall, deviation ranged from 8° to 17° for each direction (Figure 8). These results confirm that 8 directions can be reached without error, thus RPM roll can be used to interact with a Marking Menu for instance [17].

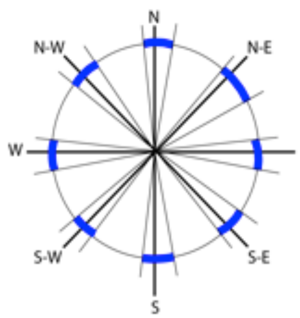

Figure 8. Rolling precision for each rolling direction

Translation: Results on translation stability, i.e. the amount of unintended rotation and roll during translations, reveal that there is on average 12° of roll and 15° of rotation while displacing RPM. There is no significant difference between Hemispherical and Convex RPM (Z=-4.29 p=0.08). While a Wilcoxon test establishes a significant difference between long and short translations (Z=-2.34, p=0.018), this difference is limited to 1° for roll. Finally no significant differences have been observed between hand postures(Z=-0.78, p=0.44).

Fatigue
The average Borg [4] score obtained is 11.72 (on a scale of 6-20). Upper shape does not significantly affect fatigue. However, fatigue measured when using the Squeeze posture is significantly higher than with other postures (Friedman $\chi^2(2)=8.46$, p=0.0144).

Summary

Our study on gesture amplitude reveals that the Hemispherical upper shape allows for the largest rolling amplitude; rotation amplitudes vary from left to right and is larger with the Squeeze hand posture. Concerning precision, roll allows for 8 precise directions; and translation stability is affected by unexpected rotation and roll. Given the fatigue results for Squeeze, we removed this posture from the following studies. From these results we define a roll threshold of 12° to avoid unintended activations and consider amplitudes up to 42° (to enable 30° rolls).

STUDY 2: 3D MANIPULATION WITH THE RPM

Taking advantage of the key benefits of RPM, we propose a technique combining RPM roll and displacement to perform 3D translations, and RPM roll and rotation to perform 3D rotation. We evaluate our solution against a dedicated commercial device, the SpaceMouse.

RPM 3D Interaction Techniques

As we use 5 DOF, applying RPM to 3D manipulation relies on a modal use: translation and rotation are performed separately. As RPM offers 2 DOF for translation, 2 DOF for roll and 1 DOF for rotation, any 3DOF task will be performed using a combination of these three gestures.

3D translation: roll & displacement

To perform 3D translation of an object, we use a position control technique: 2D physical displacement of the RPM is mapped to 2D translation of the cursor on the x-z plane in the 3D scene. The RPM front/back roll controls the elevation of the x-z plane, i.e. the y position of the plane. This technique offers the advantage to be easy to use for beginners and to support the transition to experts. Beginners can decompose a 3D translation task by performing first a 2D movement on the x-z plane, then a roll to define the y value. Advanced users can simultaneously combine displacement and roll in the same coordinated gesture to directly perform a 3D translation.

3D rotation: roll & rotation

To perform 3D rotations, two modes are possible: position control or rate control. In position control, RPM rotation and roll are directly mapped to the object 3D orientation. This mode requires clutching, as informal tests showed that to be comfortably and efficiently operated, RPM roll can be mapped to a maximum of +/- 90° rotation in the virtual scene. In rate control, the RPM roll and rotation angles are mapped to the rotation velocities of the 3D object. Informal tests revealed that position control outperformed rate control.

Study description: 3DOF pointing and docking

In this study we compare RPM with a 3D dedicated device, the SpaceMouse [27], in two separated 3D tasks: pointing and docking [21]. We do not compare with traditional mouse as it has been reported to be less efficient than the SpaceMouse for 3D interaction [9].

Tasks and instructions

We decided to conduct two sessions, each one dedicated to one 3D task: the first session consisted of performing 3D translations (3D pointing task), and the second one of 3D rotations (3D docking task). The reason we divided our experiment into two subtasks, instead of a single 6DOF docking task [21,37], is that the number of conditions for the pointing task was quite large, and combining both would make the experiment excessively long. We also wanted to study separately the performance of our device for 3D translation and for 3D rotation, and combining both would make it difficult to analyze each subtask. Previous research has proven that, even if both tasks can be carried out jointly, users usually perform them independently [21].

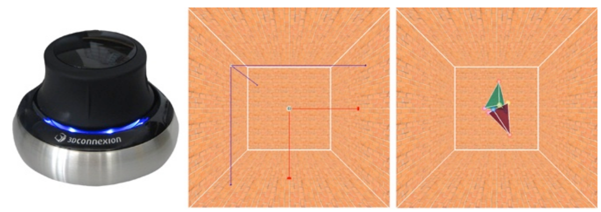

Figure 9. SpaceMouse device (left) and 3D environment for the 3D pointing (center) and 3D docking (right) tasks.

In the 3D pointing task, the participant is asked to reach a 3D spherical target in a 3D scene by translating a cursor (Figure 9). The target is displayed in the center of a cube delimiting the 3D environment. The cursor initial position is situated in 8 different directions (combining equal x, y and z translations) at two different distances (12.99 and 8.66) from the target. We implemented two different target sizes (0.5 and 1.7) to produce 4 Index of Difficulties (2.6, 3.11, 4.19 and 4.75 bits). In the 3D docking task, the user is asked to rotate a tetrahedral cursor until it fits the orientation of the tetrahedral target (Figure 9). The initial orientation is a non-trivial combination of two or three axis rotations giving 8 different orientations. In both tasks, the user starts a trial and validates the trial by pressing the space bar on the keyboard. To perform clutching with RPM the user presses the spacebar, as adding a second selection key for RPM would increase user's mental load. Therefore we did not measure selection errors for 3D docking since both clutching and validation used the same key. Participants were instructed to perform the task with their dominant hand as quickly and accurately as possible.

Apparatus

We use the same optical system and RPM settings as in the previous experiment. To define the gain value of the SpaceMouse rate technique, we carried out a number of tests. Some users found the regular gain too fast. We thus decided to test two gain values in our study: a gain similar to the default behavior of the device (best for most users after some training) and a smaller gain favouring precision over speed (best for most beginners). With RPM, we used a gain factor of 1:1 for translations and 1:3 for rotations and rolls. The experiment software was developed in C++ using Irrlicht 3D engine.

Participants

We recruited 12 participants (6 female), all right-handed, aged 28.5 years on average (SD=6). 5 were used to 3D interaction and 3 of them participated in previous studies.

Design

The 3D pointing session follows a 4x4 within-subjects design with Interaction Technique IT (RPM Hemispherical, RPM Convex, SpaceMouse Small-Gain and SpaceMouse Default-Gain) and Index of Difficulty ID (2.60, 3.11, 4.19 and 4.75 bits) as factors. The 3D rotation session has one within-subject factor, Interaction Technique, with the same 4 values than the previous session. Each session was divided into 4 blocks, each one corresponding to an interaction technique. Order of blocks is counterbalanced across participants by means of a 4x4 Latin Square. Cursor positions and IDs (for pointing) and orientations (for rotation) were randomly ordered inside each block.

Procedure

We performed a large training session for both tasks: users performed 30 trials/IT before the experiment, and then again 8 trials before each block. No constraints were given with respect to hand posture as we did not want to force hand posture on the SpaceMouse.

Collected data and statistical analysis

We logged all tracking data and measured completion time from stimulus onset. We also collected user preference and usability using two 5-point Likert scales to rate each interaction technique as well as fatigue using a 6-20 Borg scale. For the 3D pointing task, we collected 384 trials per user (4 IT x 8 directions x 4 IDs x 3 repetitions) x 12 users = 4608 trials in total. The session lasted about 73 min. For the 3D rotation task, we collected 192 trials per user (4 IT x 8 orientations x 6 repetitions) x 12 users = 2304 trials in total. The session lasted about 55 min. We used the same statistical analysis approach than in previous studies.

Results

3D pointing performance

Concerning completion time (Figure 10), a Friedman test reveals a significant difference between the interaction techniques ($\chi^2(3)=25.2$ $p<.001$). The two RPM versions (2.28 s) are faster than the two SpaceMouse versions (3.68 s) ($Z=-13.34$, $p<.001$). This result is true for any ID value and the difference grows with ID difficulty (29% for easier ID vs. 33% for harder ID). There is no significant difference between ITs concerning error rate, that was overall around 5% ($\chi^2(3)=0.28$ $p=0.96$).

3D docking performance

We found no significant difference between the two RPMs and the two SpaceMouse versions concerning completion time ($\chi^2(3)=2.3$ $p=0.51$).

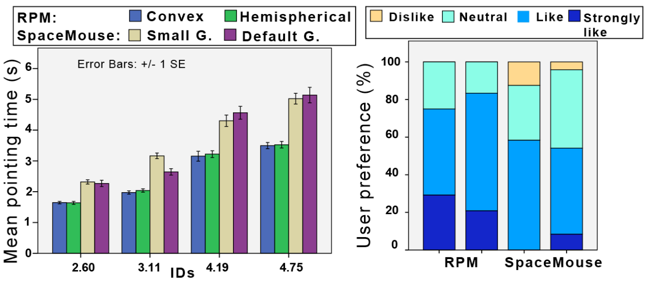

Figure 10. Mean time in s for the 3D pointing task for each IT and ID (left) and user preference (right).

User preference

There were no significant difference in terms of user preference or fatigue between both tasks; therefore we present the overall results. In terms of preference (Figure 10), 75% of the users rated Convex RPM positively (with a score of 4 or higher); 80% Hemispherical; 54% the regular SpaceMouse and 58% the slower version. In terms of usability, 75% rated Convex positively (with a score of 4 or higher); 87% Hemispherical; 45% the regular SpaceMouse and 54% the slower version. Users found that "*the SpaceMouse needs more concentration than RPM*" (p4, p9) and that "*RPM is more pleasant because I can perform the movement with a classical cursor position control*" (p6, p8, p12).

Fatigue

In terms of fatigue, there was no significant difference between the interaction techniques ($\chi^2(3)=3.50$ $p=0.32$), with an average value of 11 (6-20 Borg scale).

Summary

This study demonstrates that there is a significant difference in terms of 3D pointing time performance between the two RPM versions and the two SpaceMouse versions. RPM is 31% faster than the SpaceMouse. Concerning the 3D docking task, there is no significant difference between the different devices and SpaceMouse gains in terms of completion time. In terms of user's preference, both RPM version are considered more usable and are rated more positively than the two SpaceMouse versions. Overall, this study demonstrates that RPM can be used effectively as an input device for 3D translation and rotation and that users preferred and found RPM more usable than the SpaceMouse.

TOWARDS AN INTEGRATED VERSION OF RPM

We build on our experience in prototyping a proof-of-concept version of RPM to analyze the various technical challenges that need to be overcome to build an integrated final version of RPM.

Proof-of-concept wireless prototype

Based on our studies results, we created a working wireless Hemispherical RPM prototype with a 'ring' button all around the device. To detect the 3D displacement and rotation of RPM, we used a Polhemus Patriot Wireless tracker (7x3x2.5cm, 79.4gr.). We filtered the tracker data using a 1€ filter. To build the button we used a similar approach to the WatchIt bracelet [25]: the button consists of one resistive potentiometer (81x7.5x0.5mm) that provides up to 1024 values depending on the touch position. It is thus possible to combine the clicked position on the ring with the current RPM orientation to support multiple buttons. To interface it, we used an Arduino Fio board with a Bluetooth shield and an external battery (Figure 11). Using this prototype, we implemented two usage scenarios that we describe in the discussion section: Google StreetView and a drawing application.

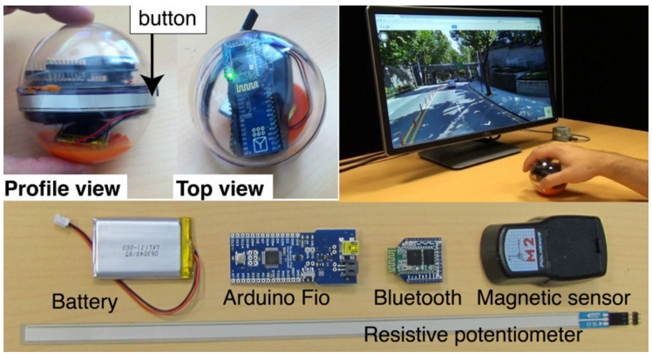

Figure 11. Proof-of-concept wireless prototype with a 'ring' button used in StreetView (top). Components (bottom).

Technical challenges

Building a final working version of RPM presents several technical challenges.

Position: to track RPM position several embedded and non-embedded solutions are possible. Embedded solutions include using magnetic sensors (although not precise enough to allow mouse-like pointing) or an embedded mini board camera similar to VideoMouse [13] (however requiring the use of a grid surface). Not-embedded solutions include using IR cameras or an underlying sensitive surface, similar to Wacom's tablets. All of these solutions would allow detecting the z-dimension at a certain level.

Orientation: to track the orientation of the device, we could use an embedded inertial measurement unit (IMU).

Contact with the underneath surface: to enable mouse-like clutching, embedded solutions include using a resistive bottom, a distance sensor or a camera as in VideoMouse [13]. This contact can be easily detected if using an underlying sensitive surface.

Hand contact: To detect when the device is held, a capacitive surface could be used. This could prevent unwanted movements of the cursor when RPM is released.

Selection mechanism: There are two main options to integrate an always-available selection mechanism invariant to rotation: an all-around 'ring' button and a capacitive surface. The 'ring' button, situated all around the device as in our working prototype, permits multi-touch input with several fingers. A more elegant solution would be to use a multi-touch surface. However, this solution would lack of haptic feedback, like on a regular button. This solution has proved to be useful for extending a traditional mouse [2,32,35] such as Apple's Magic Mouse in which it is combined with a mechanical switch. The main challenge with this solution would be to distinguish a finger touch from a palm contact or with a grasping/squeezing gesture.

Selection stability: Pressing a button could cause RPM to move. To ensure RPM stability, we should favor a selection mechanism positioned all around the device: a finger pressure would then exert perpendicularly to roll direction.

Device repositioning: even if the low center of mass of the device allows auto-repositioning, the device wobbles when released. To limit this oscillation, in particular when switching between the mouse and the keyboard, a solution based on a self-balancing mechanism coupled with the inertial measurement unit could be integrated. The main challenge would be to fit the hardware within the RPM volume.

DISCUSSION

All-in-one device

Our paper illustrates that RPM constitutes an all-in-one device capable of handling 2D and 3D tasks. Our studies demonstrate that it performs 31% faster than the SpaceMouse for 3D translation. Most users preferred the Hemispherical upper shape for 3D interaction. Our work initially explores the many other possibilities for such a novel device based on the combination of translation, roll and rotations as illustrated in the usage scenarios.

Other usage scenarios

While our main motivation to build RPM was to create an all-in-one device for 2D and 3D interaction, we explored other usage scenarios that could benefit from RPM key features. We carried out a one-hour design session with 15 participants to collect application scenarios. Many participants came up with use cases related to 3D interaction, ranging from 3D games to 3D editing. They also gave numerous ideas on a large variety of applications: in video editing; music composition; graphic drawing; web browsing; map navigation; marking menus; or exploring large datasets. For each idea, participants mapped different functions to the RPM degrees of freedom. For instance, in a map application, translation is used to translate the view and roll to adjust (rotate left/right, zoom in/out). In a drawing application, translations are mapped to drawings, rotations to the selection of the drawing colors and rolls to thickness and type of drawn lines. This design session illustrates the possible range of usage applications for RPM.

Design guidelines for rolling devices

Our studies allow us to sum up a set of design guidelines for the future adoption of rolling devices. The hemispherical upper shape has proved to be the best in terms of roll amplitude. When mapping control to roll and rotation gestures, designers should take into account the orientation as it enables different amplitudes. Roll gestures can be performed precisely in at least 8 directions and a roll threshold of 12° should be used to avoid false activations. For 3D pointing, using compound gesture is the most efficient. For 3D rotation, position control could be coupled with rate control as in [30].

Device instability

Unlike the traditional mouse or previous tilting devices such as the Rockin'Mouse, which have a flat bottom, the RPM bottom is hemispherical: the device is thus not stable. This is particularly true in two cases: when the device is released, as it wobbles, and when the device is moved, as it rolls accidentally. In the first case, a simple solution is to detect when the user is holding the device. The device can then be "turned off" when no touch is detected. In the second case, when the user moves the device on a flat surface like a mouse, an appropriate threshold must be used to avoid false positives due to unexpected roll.

Z-dimension

We did not explore this dimension in our paper as we believe it introduces the issue of fatigue. However a sporadic use is possible, for instance holding RPM on the palm during a presentation. In this context RPM could be used to perform mid-air gestures to control slides. We plan to further explore this perspective in the future.

LIMITATIONS AND FUTURE WORK

Our exploration was limited by the use of markers on RPM, by the tracking technology, by the lack of selection and clutching mechanism and by the separation of 3D tasks. The use of IR tracking allowed us to precisely measure all the gestures. As a counterpart we had to carefully place IR markers on the Roly-Poly Mouse in an unobtrusive way. Even if these markers may have had a minor effect on user's gestures, we plan to validate our findings with a wireless marker-free prototype. In addition, our experiments did not evaluate RPM in a 2D pointing task nor the use of an embedded selection and clutching mechanism. In the future we plan to compare RPM with the regular mouse for 2D pointing and evaluate different solutions as discussed above, such as the 'ring' button used in our proof-of-concept prototype. Concerning RPM size, currently based on the regular mouse size, it could be interesting to explore a smaller version of RPM where the user can manipulate it while resting the hand on the table. Finally, we plan to carry further studies on the performance of RPM for an integrated 6D-docking task to evaluate the impact of mode change.

In the future we plan to evaluate 2D pointing with RPM against a classical mouse as said earlier. A long-term study on comfort is pertinent to further explore fatigue issues. We will further explore the design space of RPM compound gestures by proposing and evaluating novel techniques for some of the aforementioned applications, for instance to manipulate graphical items orientation and position as in [16]. Finally, we plan to explore mid-air and free-roll gestures and propose novel GUIs for RPM, such as circular menus or widgets.

CONCLUSION

In this paper we present the design of a novel input device, the Roly-Poly Mouse (RPM) combining the advantages of the mouse and of 3D devices by allowing three types of gestures: translation, roll and rotation. To enable stable 2D pointing with RPM, we propose a roll correction algorithm. We identified preferred RPM upper-shapes and most frequently adopted hand postures through a preliminary study. Based on these results, a first study on gestures amplitude and stability reveals that our device allows large and precise rolls to be performed. In a second study we compare the two versions of RPM with a popular 3D device, the SpaceMouse, in two 3D tasks: pointing and docking. We propose a novel compound gesture for the 3D translation based on rolling and displacing the device. Results reveal that RPM performs 31% faster than the SpaceMouse in terms of translation time and equivalently in terms of rotation time. Users preferred Hemispherical RPM for 3D interaction. Finally, we used our experience in implementing a proof-of-concept prototype to identify the various challenges to overcome to build a final integrated version of RPM. To sum up, RPM is an all-in-one device that removes device-switching costs, improving the workflow of users.

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