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Näprä — Affordable Fingertip Tracking with Ultrasound

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Abstract

In this paper we present Näprä, a novel tracking device suitable for fine motor interaction. The motivation for building the device was the need to track users' fingertips in an immersive free-hand drawing environment. Such tracking offers significant benefits for fine-grained artwork. Out of the numerous tracking methods ultrasound was chosen because of its affordability and low computational requirements. The design and implementation of both the hardware and software are discussed in detail in their respective sections. The device was evaluated in practice by two user tests, the first involving ten professional artists and the latter seven ordinary users. The results obtained in the tests are presented to reader as well as some directions for future work.

Categories and Subject Descriptors (according to ACM CCS):
H.5.2 [User Interfaces]: Input devices and strategies
H.5.1 [Multimedia Information Systems]: Artificial, augmented, and virtual realities
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1. Introduction

Immersive free-hand drawing as an art form has received some attention since the late 90's. The best known examples of such research are conducted by Schkolne [SPS01] and Keefe [KFM*01]. Both groups have used tangible interface elements in their drawing systems. The work presented in this paper belongs to the same frame of reference of immersive art: the underlying goal was to help artists better express themselves in a virtual environment using natural means of interaction.

As an artists' tool a stylus or a wand-like device allows for only limited fine motor interaction, greatly limiting the rich variety of gestures achievable with a human hand and fingers. Especially the fingertips are capable of performing fine-grained tasks. To track the exact position of the user's fingertips in a virtual environment there are two possible approaches. The first, direct method would be to track the fingertips using the default tracking system of the particular virtual environment. However, the fingertips differ from the usual tracking targets presenting challenges to the tracking system. A serious obstacle is the large number of fingertips that need to be tracked separately.

The other approach is to track fingertips in another reference frame using a secondary tracking system. This method has been often used with data gloves to track the palm of the hand with the primary — often magnetic — tracking system and from this tracked and therefore known reference frame the fingertips. A low-cost dataglove provides only rough information about the bending of the fingers, which is less than satisfactory for artistic use. To be able to capture the full spectrum of the fine motor movements of the artist a better solution is required. High-end datagloves provide the needed functionality but on the other hand often cost several thousands of dollars thus making them unsuitable for small-scale projects.

The two practical affordable techniques for accurate fingertip tracking are video and ultrasound. Both have been used in numerous virtual reality setups for large scale tracking and to a certain extent they share the same characteristics: occlusion and environmental noise (light or sound) hurt the accuracy. Optical tracking has been succesfully used for fingertips [RB04] [PCI03] [VRC99] but the inherent problems of the technique still remain partially unsolved. A great advantage for optical tracking is that the user only needs to wear simple markers or in the best case nothing extra in her

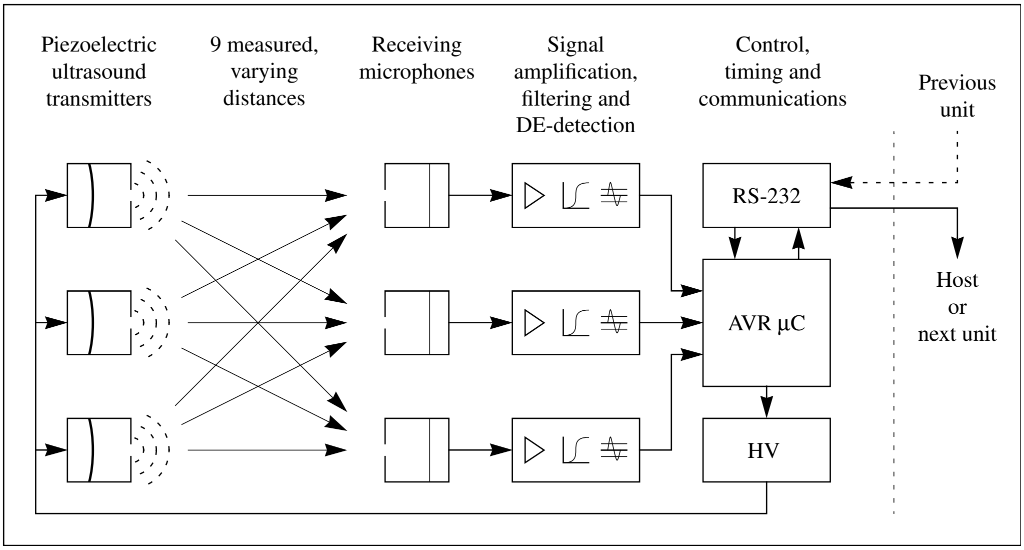

Figure 1: *The basic structure of the Näprä fingertip tracker.*

fingers. The significant downside of the camera-based approach is the heavy image processing associated with video frames. A system with a slow CPU or little memory such as an embedded device might not be powerful enough for the computations.

In addition to position tracking, some applications benefit from the availability of exact contact or "pinching" information between the fingers. This cannot be deduced from the fingertip positions as finger sizes differ from person to person and the required absolute accuracy is in the order of 0.1 mm. To obtain this information, specific sensors capable of measuring the contact have to placed directly at fingertips.

A prototype implementation called Näprä was built to meet the complex needs of fingertip tracking. Näprä incorporates ultrasound tracking and pinch detection for the first three fingers plus two command buttons for the remaining two fingers.

2. Hardware design and implementation

Näprä uses dual-threshold ultrasonic time-of-flight (TOF) measurements to track the fingertips. While simple in principle, ultrasonic TOF measurements are usually considered troublesome for virtual environment tracking because of the presence of echoes, occlusion, the varying speed of sound, sensitivity to external noise and especially the inherent lag associated with the method. In Näprä, some of these challenges are not relevant and the rest are met to a large extent.

2.1. Design considerations

Due to the very small range when tracking fingertips from the palm, it is easy to generate strong enough ultrasonic pulses from the transmitters to overcome ordinary outside noise. The small range also provides great attenuation to outside echoes, as the relative distance for them is orders of magnitude greater than that for the direct signal. Local echoes from the hand are quite weak to begin with and are totally avoided by detecting the first wave of the ultrasonic pulse. The geometry of the fingers in hand is such that occlusion of the receivers from the transmitters can be largely avoided through proper placement of the transmitters.

In indoors environment, the speed of sound varies about 1% from the nominal value of 343 m/s. As this error is relative to the magnitude of the measurement distance, the worst case error is less than 1 mm. The actual tracking result is a function of the distance measurements and the placement of the transmitters, but for a typical system, the final error resulting from the variation of the speed of sound is in the order of a few millimeters. Furthermore, this error is systematic, so that if a fingertip is used to control a virtual instrument, this merely causes a negligible offset to the actual and measured positions. Finally, should this error become of concern in some application, the speed of sound could be measured in real time by fixing one of the receivers of Näprä to a known position in relation to the transmitters.

The fundamental limitation for straightforward time-of-flight measurements is the very time necessary for the sound pulse to reach the receiver. This limits the real-time behaviour of the system. However, in Näprä the measurement distances are so small, that the measurement times are less than in most other tracking methods. For a single hand, distance measurements can be performed at 1000 Hz rate resulting in at least 300 tracking results per second for a finger. This figure is much higher than the typical system update frequency, so the accuracy can be improved by filtering the results with no performance penalty. For two hands, the rate is lowered to 100 results per second to allow the direct tracking pulses from the other hand bypass the other before a measurement is initiated.

2.2. Operating principle

The operating principle of Näprä is straightforward. Three non-colinear transmitters send an ultrasonic pulse in turns and the time of flight to the receiver, which is also the tracking target, is measured. From the three times of flight and assumed speed of sound, three distances are calculated and from these and the known placement of the transmitters, the location of the receiver relative to the transmitters is solved. There are always two solutions, which are mirror images relative to the plane the transmitters define, but in Näprä the fingertips can only reside on one side of this plane, so there is no ambiguity. To get the position of the tracking targets in an external coordinate system, the position and orientation of the transmitter array relative to this external system has to measured and applied outside Näprä. The overall structure of the device is shown in Figure 1.

To measure the time-of-flight, an ultrasonic pulse has to be generated and detected. To differentiate between the actual signal and spurious outside noise, a dual-threshold detection system was developed. As the ultrasonic transducers used for the pulse generation are very resonant at about 40 kHz frequency, they generate a ringing waveform of exponentially decaying sinusoid from a single excitation pulse. By detecting both signal transitions above a positive threshold and below a negative threshold, this sinusoid causes both to trigger with a very specific time difference of half wave. On the other hand, random noise which is rarely strong enough to trigger either detection, is highly unlikely to cause a dual trigger with this same time difference. Therefore the dual-threshold detection is very reliable and can be used to reject erroneous measurement results.

When the thumb makes contact with either the index or middle finger they form a closed circuit, which can be used for detecting the pinch gestures. The distance measurement results together with pinch and button activity information are transmitted to a host computer via a serial link for the actual tracking calculations to be performed.

2.3. Implementation

The Näprä was realized as a two-sided printed circuit board small enough to fit in the palm, and containing all the necessary electronics except the transmitters, receivers and buttons. All the operations are controlled by a small 10 MHz AT90S2313 microcontroller. To generate short but strong ultrasound pulses, the transmitters are driven with a step function, namely their internal capacitance is relatively slowly charged to the operating voltage of about 100 V and then abruptly discharged with a small transistor. This high voltage is generated onboard by the microcontroller with a simple flyback converter. The receivers are small electret microphone capsules, the signals of which are first amplified and roughly filtered with an operational amplifier and then detected with a pair of comparators for each. The microcontroller transmits pulses from each transmitter and measures the time of flight of the sound to each receiver. The data is transmitted serially through an RS-232 level converter to the host computer. To use two Näprä units instead of one, the microcontroller is also capable of receiving serial transmission from a previous unit, to further transmit it to the host, and to simultaneously synchronize the operation between the units.

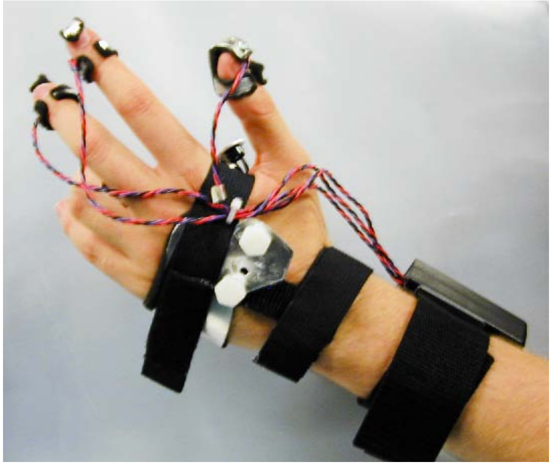

Figure 2: *Näprä from the back of the hand. Notice the white plastic screws used for attaching a magnetic tracking sensor.*

To remove the directionality from the transmitters as well as from the receivers, washers were glued directly on them. These washers have a 4 mm aperture, which is small enough to force them to operate with an omnidirectional sensitivity. This also results in some decrease in signal level and sensitivity, which in this case were not limiting factors.

2.4. Ergonomy

From the beginning one of the design goals was to make Näprä suitable for a variety of users. The varying size of hands and fingers is a fundamental problem that influenced the construction of the actual device. Other considered factors were the height and the handedness of the user. The latter two problems were dealt with by making the wires long enough and building two Näpräs, one for each hand.

To accommodate different hand sizes the straps attaching Näprä to the hand were made adjustable, as seen in Figure 2. The thimbles containing the ultrasound microphones were made of flexible aluminium so that they could be bent to slightly different shapes (Figure 3). The inside of the thimbles is padded with soft plastic. Had we used a glove as the basis for Näprä it would have been way more difficult to accommodate the differences between individuals. The plate holding the command buttons is adjustable as well.

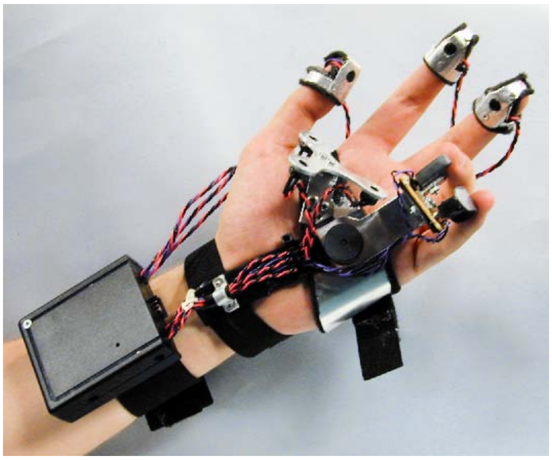

Figure 3: *Näprä from the palm side of the hand.*

3. Software Implementation

The Näprä input was integrated into our software as a plugin. The plugin code decodes and filters the raw data coming from the Näprä. As far as the application is concerned Näprä appears as a combination of a minimal data glove (the three finger positions) and a mouse (Näprä buttons map to mouse buttons).

3.1. Signal Filtering

The TOF values need to be filtered before they can be used by the appliction. This filtering is done in the decoder library. This allows easy experimentation with different filtering approaches. There are three kinds of disturbances in the TOF values:

1. One value in the TOF pair is missing or broken. This happens when either the raising or decaying TOF value cannot be measured reliably.
2. Sudden peaks in TOF values. This typically happens in difficult measurement conditions before the signal is completely lost.
3. Complete loss of TOF values. This happens when receivers are occluded by fingers or out of the maximum range.

To counter these problems we have developed a filtering algorithm that works in multiple steps:

1. Remove all TOF values that are known to be incorrect (outside the allowed limits). This step removes the worst occlusion artifacts without causing any latency.
2. Reject incoming TOF values that are too far from the previous known value. If after some time the values do not return back to the expected range, then the new values are accepted. This step removes sudden peaks from the signal without causing any latency.
3. Perform low-pass filtering on the signal. The low-pass cut-off frequency is adjusted dynamically based on the signal quality estimations from previous steps. This step introduces variable latency to the system. In optimal situation the latency is in the order of one or two samples. In the worst case the latency may be as high as 0.3 seconds.
4. Join the raising and decaying TOF values together. The one with lower quality plays smaller role when determing the final TOF value.

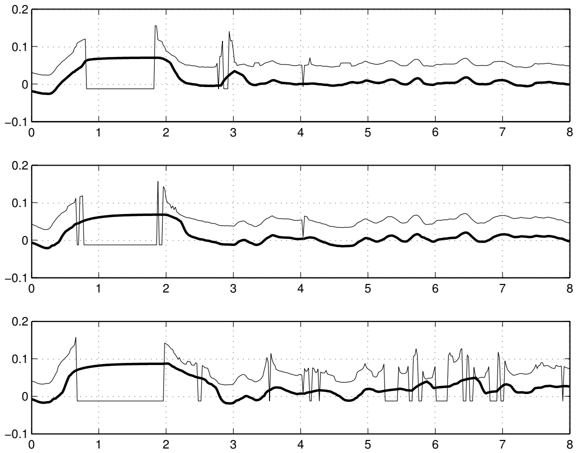

Figure 4: *The effect of filtering on the three TOF values of a finger. In each graph the thin line represents the original values and the thick line represents the filtered results. An occlusion takes place at 1–2 s.*

The effect of this filtering can be seen in Figure 4. While this filtering can make the signal significantly smoother it can introduce problems when calculating the location of the receivers. To calculate the location of one receiver we need to use three TOF values. If one TOF value is badly wrong the 3D location cannot be calculated reliably. This calculation basically involves finding the intersection of three spheres, where each sphere represents distance from a transmitter. If the radius of one sphere is incorrect the intersection point starts to move uncontrollably. In the worst case the calculation becomes impossible or the result is completely wrong.

3.2. Integration

Näprä is connected to the computer with a serial cable. We have a small library that decodes the incoming data stream and filters it into a format that the drawing application can use. This library does not deal with the actual serial port, which is handled by another library. This modular approach is intended to ease porting to different operating systems — only the serial port code needs to be re-written.

Näpräs are connected to a Linux PC that collects the data, decodes it and sends it over the network to the graphics computer. The large-scale hand motion is tracked with a magnetic motion tracker (Ascension MotionStar) and the motion of fingers relative to hand is tracked with Näprä. The plastic screws used for attaching the magnetic sensor can be seen in Figure 2. The presence of small amounts of aluminum does not significantly affect the large scale tracking, because MotionStar operates with DC fields instead of AC. The frame between the magnetic sensor and the ultrasound transmitters is rigid, so there is no need for per-user calibration when calculating the absolute position of the fingertips. For higher level interaction such as gesture detection a customizable calibration scheme would be necessary because of the different hand sizes.

3.3. The Immersive Drawing Software

Näpräs were developed for the needs of an immersive drawing software. The application enables artists to draw and to animate 3D shapes. There are numerous tools for creating and manipulating the graphics: polygon tubes, lines, particle clouds, animation controls and transformation tools.

The application has two modes: a real-time drawing mode and control mode where the tools are selected and configured. In the control mode the user can use a "kiosk" (see Figure 5) to select tools and to set their parameters. In the drawing mode the artist should work in close contact with the art and the only extra visual information is a minimal 3D representation of the current tool and its working radius.

At first we had only wand control for the application. We found out in a previous study [MRTI04] that artists cannot use all of their skills with the wand. Näprä interface was developed to overcome the limitations of the old wand interface.

3.4. Interaction Methods

The roles of the different fingers are based on how well people can control a particular finger. The first three fingers (thumb, index and middle finger) are easy to control independently with high precision. The ring finger and little finger cannot be controlled with equal precision. They are also mutually linked. This basically implies that the ring finger can be used only when other fingers are not active. The little finger can be used even when the first three fingers are active.

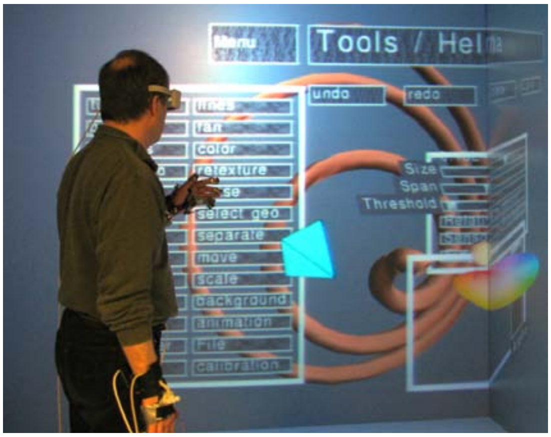

Figure 5: *An artist using the main menu of the drawing software.*

In the drawing mode the little finger button is used for activating the tool. The tool is active as long as the button is pressed. In the control mode the little finger is used for activating widgets (menus, buttons, sliders etc). The first three fingers are used for controlling the active drawing tool. In the case of the polygon tube the user can resize and shear the shape of the tube, for most other tools the radius can be adjusted by moving fingers closer and farther together. In the control mode the contact of the first three fingers can be used for activating widgets, performing exactly like the little finger.

The two-way button under the right hand ring finger is used for toggling between control and drawing mode and for navigation. In the left hand the same button is used for triggering quick edit menus for the right and the left hand.

The drawing application is completely two-handed. Both hands can use all the tools, making the system suitable for both right- and left-handed users. The tools can be used at the same time. This enables creative two-handed interactions between different tools. For example the user can grab a sculpture with a motion tool, hold the object in one hand and add color with a spray tool.

4. Practical evaluation

Two different user tests were conducted in order to test Näprä in real-world use. The first one involved ten professional artists (painters, graphic artists and sculptors) that used the device for creating works of art. This test was the continuation of a previous study that was conducted using an ordinary wand-like input device [MRTI04]. The latter test was a low-level usability test and provided additional results about the basic functions of Näprä.

4.1. Testing with professional artists

All ten artists were committed to create an artwork, using the new possibilities of making art in immersion. They had previously worked with a wand for two days and this time they spent two days drawing with Näprä. Although there were simple exercises included in the tutorials for both interfaces these free art sessions cannot strictly be categorized as traditional user tests. However, the processes of artists involving working with two Näpräs (one in each hand) provided us valuable information about the limits and possibilities of the output. In Figure 6 there are two screenshots of one of the works created.

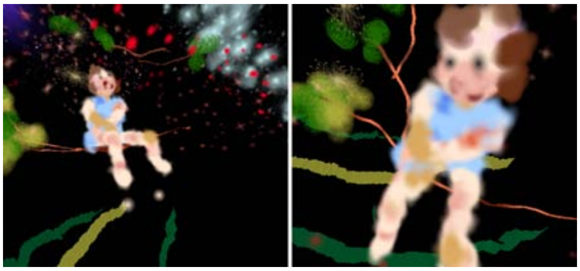

Figure 6: *A work of art drawn with two Näpräs.*

The newborn Näprä prototype was not thoroughly tested before the artistic use. For example the orientation of the tube shape was determined strictly by the three tracked fingers. Unfortunately the artists had already become familiar with the wand-based orientation, which had automatically followed the direction of the hand movement. Better control over the spatial shape provided more alternatives but the obligatory maintaining of the shape proved laborous, and the artists tended to unwittingly produce flat tubes by drawing with the profile in a sidewards position.

The finger activity confused many of the artists since they typically are used to rest their fingers on the body of their pen or brush. However, most of them learned to use the device during the sessions and were pleased with the new possibilities offered by vivid traces. On their second day with Näpräs two of the artists already felt that they could control the output rather well. The two artists in question had previously played violin or piano which can be seen as a contributing factor.

Not only the orientation, but the size of numerous tools was tied to the user's fingertips in real time. This was definitely a central advantage of Näprä. In addition to controlling the sizes of mesh profiles or particle clouds while drawing, the artists got used to instantly defining the active areas of edit operations such as erase, colorize, select and move.

With two Näpräs it was possible to have a separate tool in each hand which considerably increased the power of the interface. Many of the artists spent long periods working with just a pair of two tools: particles and eraser, mesh and moving tool or particles and mesh. Not always did they fully use both hands but the work still progressed well. Although they had the option of going back to the traditional wand, in the end nobody was willing to do it.

4.2. Low-level usability test

The most important goal for this test was the evaluation of a new user interface concept involving Näprä, not the device itself. During the seven test sessions we were able to make several relevant observations on the usability of Näprä as well. Compared to the previous tests the user base was very different: instead of skilled artists the users were less experienced with self-expression but on the other hand more familiar with information technology.

The test consisted of four parts. After the initial introduction and trying out the system followed the performance tests that measured selection speed. In the third part the users were given five simple drawing tasks such as a flower or a bicycle. The last part was a semi-structured interview about the immediate observations and feelings of the users after completing the tasks. The latter two were the most relevant for the topic of this article. On the whole a single session lasted for approximately an hour.

The most important observation was that the users seemed to learn to use Näprä very fast. Their actions were a little shaky and cumbersome in the first drawing tasks but surprisingly fluent already in the last two or three ones — even though the session was so short. Some of the users started to independently exploit subtleties such as the thickness and direction of the tube. Only one user reported experiencing minor physical stress during the test and according to the interview the overall attitude of the attendants was highly positive towards the system. One of the users was particularly small-handed but the adjustability of the thimbles was enough to accommodate her as well.

Especially during the first tasks most users ran into a situation where they were uncertain about the function of the different buttons and pinches: when do I pinch and when do I click? They overcame their confusion eventually but the mere existence of the problem suggests that the conceptual model of the interface is not completely intuitive. The limited tracking resolution of both Näprä and the magnetic tracker caused additional nuisance which, however, bothered the users rather little. As noted already in the first tests the tracking accuracy might not be the most central factor for artistic expression [MRTI04].

5. Results

The overall impression of Näprä has been mainly positive. It has enabled the use of enhanced interaction methods that go beyond the capabilities of the traditional wand. The remaining technical and conceptual problems still need to be addressed in order to fully utilize Näprä's potential.

5.1. Strengths of Näprä

Principally Näprä gives an intuitive control over the spatial fingering of a virtual primitive, as if fingering an egg or matchbox or such. This kind of action happens naturally without mental strain. Adjustable buttons under the weak fingers, with solid roles, give reliable response purely by muscular memory, without looking down or digging around. Two-handedness multiplies these strengths: the human body has no serious problems in transporting learning from one hand to the other and working simultaneously with both hands.

In the low-level usability tests many users experienced a sense of control with Näpräs, when compared to the wand interface. This kind of experience makes the technology more acceptable to the users and supports the artists' self-confidence when working, ultimately resulting in more pleasant interaction.

Low price was one of our original design goals. The components of Näpräs were extremely cheap, while the research, design and construction took time and a lot of manual work. With proper manufacturing techniques Näpräs could be produced at a very low cost. Since the signal filtering does not need heavy computation Näprä can be used with low-end computers, even mobile devices.

Näpräs have been in use for almost a year, with minimal hardware or software failures. Once a visitor stepped on one Näprä, but it was restored to working condition by twisting the bent parts to their original shape. This implies that the simplicity of the design has had a positive impact on the reliability of the system. In fact Näpräs are probably the most reliable components in our VR installation.

5.2. Problems of Näprä

The actual tracking resolution achievable with the drawing system is a combination of two devices: Ascension MotionStar and Näprä. Large-scale tracking errors are created by the limited accuracy of the magnetic tracker. The errors are acceptable in the range of approximately 0.5–1.5 m from the transmitter. Outside of that sphere the errors grow rapidly and accurate drawing becomes impossible. The most notable artifacts are incorrectly bent and wavy lines. There are methods for correcting the systematic error [Bry92] [Zac97] but ultimately the magnetic tracking technology itself sets the hard limits for the accuracy. The internal filtering of MotionStar tackles the noise problem well but introduces additional lag that affects the user experience to a certain extent.

The tracking errors of Näprä are small compared to the ones introduced by the magnetic tracker. However, they can be as significant because of the scale of the fine motor movement of the fingers. In practice The worst problem that was encountered was occlusion: even some natural finger positions introduce situations where one finger shadows the microphone of another. The other significant source of inaccuracy was the location of the transmitters. The "propeller" seen in Figure 3 was positioned so that the tracking accuracy would be best when the fingers are naturally bent. Unfortunately this lead to a situation where very large finger movements were hard to track because the fingertips reside almost on the same plane as the transmitters. Additionally, when the fingers are very close to the palm the transmitters slightly limit their movements.

5.3. Further work

The overall durability and ergonomic design of Näprä need further attention should it be aimed at a larger market. There are numerous weak wires that are likely to get stuck on users' clothes or to the other Näprä. A proper industrial design with less wires — possibly even a wireless version — and durable construction would obviously make the device more attractive for a wider user base. Unfortunately at the moment we are lacking the resources necessary for such a design project.

To improve the tracking accuracy both software and hardware need to be improved. On the hardware side a better layout for the transmitters would very likely improve the results. To overcome the problem of large finger movements the transmitters ought to be positioned in a different place and at a different angle. On the software side better filtering methods should be examined. Two additional solutions have been considered: limiting the active area of the finger movements and buildind a mathematical model of the hand. The latter solution would rule out those positions that are clearly impossible for normal human fingers. For example the forefinger usually moves only in two dimensions.

The technical problems such as tracking accuracy and ergonomics are not trivial to tackle but the most important area for further development is the user interface. Näprä facilitates a great variety of interaction methods such as gesture recognition and two-handed interaction. At the moment the interface provides only limited support for such methods.

6. Conclusions

The ultrasound tracking of fingertips turned out to be a practical technique. The two prototype Näpräs that were built of affordable components proved the concept and were actually useful in real use cases as well. The achieved accuracy was satisfactory in a short range but less so with large finger movements. The inherent problem of occlusion was not totally solved either. Both of these can be overcome to a great extent with better transmitter placement.

In practice Näprä was used as an input device for an immersive drawing application. The observations made in two different user tests suggest that the level of control provided by Näprä offers significant improvements in interaction when compared to typical wand-like input devices. However, to fully exploit these new possibilities the user interface paradigm still needs to receive considerable attention.

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