

# Inverse Kinematic Infrared Optical Finger Tracking

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## Abstract

Human hand and finger tracking is an important input modality for both virtual and augmented reality. We present a novel device that overcomes the disadvantages of current glove-based or vision-based solutions by using inverse-kinematic models of the human hand. The fingertips are tracked by an optical infrared tracking system and the pose of the phalanxes is calculated from the known anatomy of the hand.

The new device is lightweight and accurate and allows almost arbitrary hand movement. Examinations of the flexibility of the hand have shown that this new approach is practical because ambiguities in the relationship between finger tip positions and joint positions, which are theoretically possible, occur only scarcely in practical use.

**Keywords:** Optical Tracking, Finger Tracking, Motion Capture

## 1 Introduction

For many people, the most important and natural way to interact with the environment is by using their hands. Since the advance of virtual reality, a number of methods have been proposed which enable human computer interaction via hand gestures [SZ94, Stu92].

We propose a new finger tracking device (cf. fig. 1) where only the positions of the palm and of

the fingertips are tracked. All further parameters, such as the angles between the phalanx bones, are calculated from that. This approach is inverse compared to the current glove technology and results in much better accuracy. Additionally, the device is lightweight and comfortable to use.

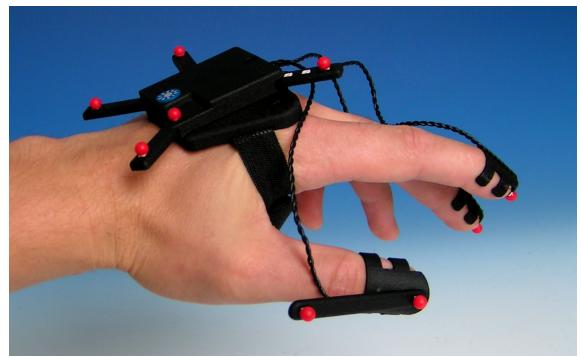


Figure 1: The inverse kinematic infrared optical finger tracker

### 1.1 Related Work

While even a standard keyboard can be seen as an input device based on human finger motion, we consider only input methods that allow – to some extent – arbitrary hand movements. This is mainly needed for three-dimensional input for virtual (VR) or augmented reality (AR) systems. We can distinguish between purely visual gesture recognition [Gav99] and glove-based input [LaV99]. Gloves are physically attached to the user’s hand and measure values for the move-

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ment of the fingers, depending on the technology used.

The main measurement concept in commercial hand tracking systems is to measure the angle of every finger joint directly by either electrical or optical sensors [LaV99] and then apply forward kinematics to calculate the pose of the joints and of the fingertip. This forward calculation propagates and accumulates measurement errors from every joint towards the fingertip, thereby amplifying them. As a result, pointing accuracy at the fingertip is very low. This may be acceptable for pure VR applications. Yet, for AR, where the real world can be seen and sensed in addition to the virtual world, the resulting misalignment destroys the user's impression of realism and immersion.

There are several reasons, why data gloves did not yet break through in VR applications either. Firstly, for the measurement of finger joint movements, the measurement device needs to be attached very tightly to the human hand, or the errors will get too big. Secondly, every hand anatomy is different. Thus, in principle, gloves should be custom-made for every user. In reality, usually only few different models are available and the user needs to choose the one that fits best [LaV99]. Further problems are related to ergonomic issues: Putting the glove on and off as well as wearing the glove is generally cumbersome and uncomfortable since it has to fit tightly. Additionally, this leads to sweating and raises questions of hygiene since proper cleaning is hardly possible due to the electronic and mechanical parts involved.

## 2 Proposed Solution

In this section we describe how it is possible to use inverse kinematics for calculating the finger poses. We provide a short insight into the anatomy of the human hand and show how this can be used to calculate the pose. Finally we show how user specific calibration is carried out.

### 2.1 Anatomic Layout of the Human Hand

The human hand consists of 19 bones, plus eight bones that build the carpus but are not relevant for finger motions. Every finger consists of four

bones, while the thumb has only three. The thumb in general has an exceptional position and is not included in the following examinations. For the fingers, three bones (phalanxes) are movable independently and form the actual finger, as it is visible from the outside. The joints between the first and the second and the second, and the third phalanxes are hinged – with one degree of freedom each. The third (base) joint has two degrees of freedom [LWH00]. Thus, altogether, the motion of an individual finger can be described by four parameters.



Figure 2: Natural finger movements

According to Littler [Lit73] the bone lengths from the outer phalanx to the metacarpal bone follow the fibonacci sequence i.e. each bone length scales with a factor of 1.62 to the outer neighbour. [PFSC03, HD02, Lit73] could not support Littler's theory but did not find a better relationship either. Thus, we accept Littler's thesis in this work.

Littler also considered the joint angles of the finger and claims an equiangular bending. Figure 2 shows some natural gestures which contradict this at least for the finger base joint. This joint can be moved independently.

### 2.2 Kinematic

As discussed above, most current finger tracking systems use forward calculations to infer the position of the fingertips from angular measurements at each phalanx – yielding poor accuracy. In our approach, we measure the position of each fingertip directly, using an optical marker. We then calculate the pose of the fingertip by reversely determining the position and orientation of each phalanx using inverse kinematics. As a result, the tracking system provides not only the fingertip position but also the pose of every single phalanx – which is helpful for hand visualizations – and the pointing direction of the entire finger, as required for interaction with virtual environments.

Getting the orientation of the outer phalanx is also

important to correctly calculate the tip position, since the marker can only be attached to the finger with an offset (see 2.3). The outer phalanx orientation determines the direction of this offset.

### 2.2.1 Pose of the Fingers

We have examined the flexibility of the fingers and the relative bends of the different joints in typical finger postures. Figure 3 shows that the bending angle  $\alpha$  between outer-most and middle phalanx maintains a well-defined relationship to the bending angle  $\beta$  between the middle and inner phalanx (cf. fig 4). This relationship can be approximated by a quadratic equation, yielding the ratio  $q_{\alpha,\beta}$  for the first two angles:

$$q_{\alpha,\beta} = 0.23 + 1.73d + 1.5d^2$$

where  $d$  denotes the distance between the base joint and the fingertip relative to the maximum distance (finger length).

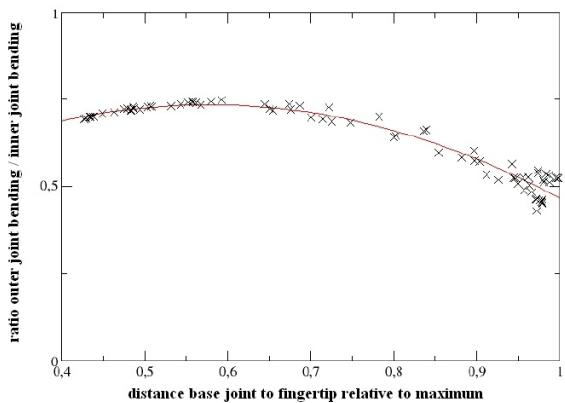


Figure 3: Relative angles of the first and second finger joint

We can compute the pose of every single phalanx by solving a system of equations for finger motion according to the anatomical model from section 2.1: The pose of the base joint (6 DOF) is given by the tracking target on the back of the user's hand (see section 3 for calibration). The position of the fingertip (3 DOF) is directly measured, defining a line  $l$  from the base joint to the marker with length  $d$ . Since finger joints  $\alpha$  and  $\beta$  are hinged and the joint angle does not allow torsion, all bending occurs in a plane that is defined by line  $l$  and the vector pointing upwards from

the back of the hand. The pose and orientation of the three phalanxes within the plane can be computed from ratio  $q_{\alpha,\beta}$  and Littler's Fibonacci ratio of phalanx bone lengths [Lit73, PFSC03].

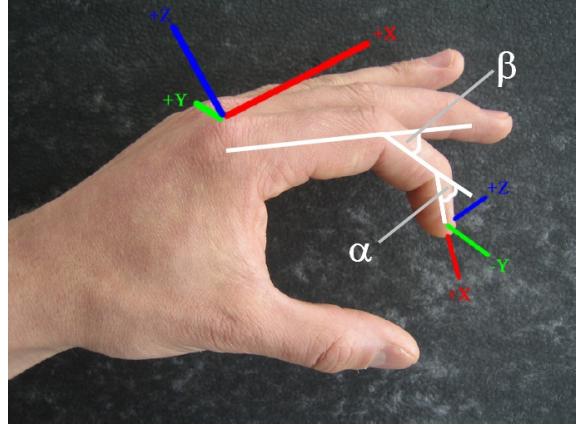


Figure 4: Hand coordinate system with finger coordinate system and bending angles

Figure 4 shows the hand coordinate system as it is defined by the geometry of the hand. The base joint position of the index finger was chosen as origin. It also illustrates the bending angles  $\alpha$  and  $\beta$  and the finger pose.

### 2.2.2 Pose of the Thumb

The thumb has an exceptional position compared to our fingers. The correlation between the joint angles as shown in fig. 3 is not valid for the thumb. Furthermore, it is much more difficult to determine the base joint position. We solved this problem by adding a second marker to the thumb as seen in figure 1 such that the outer phalanx can be measured in five degrees of freedom. The remaining two phalanxes are fitted between the measured outer phalanx and the estimated base joint position. For the length of the thumb we assume that the two phalanxes have equal length [Lit73, PFSC03].

The orientation of the bending plane is given by the base joint position and the two markers. If these lie approximately on a line, we guess a likely orientation.

### 2.3 Marker Position

The position of the marker at the fingertip plays an important role. Figure 5 shows several options

for placing the marker: on the finger nail (a), directly in front of the fingertip (b), or slightly underneath the fingertip. In most applications, maximum convenience would be provided by placement (a). Yet, the graph in Figure 5 shows that, for this setup, it is not possible to unambiguously determine joint angles below  $25^\circ$  from the measured distance  $d$  between the marker and the base joint: function (a) is not invertible in that interval. Accordingly, we choose a marker position directly on the long axis of the outer phalanx (b). Placing the marker below that axis as in (c) yields a function (c) that is also invertible – especially for small angles. The slope of the function is a direct indicator of how stably angles can be calculated. Nevertheless position (c) reduces the usability in a way that is unacceptable even for VR tasks.

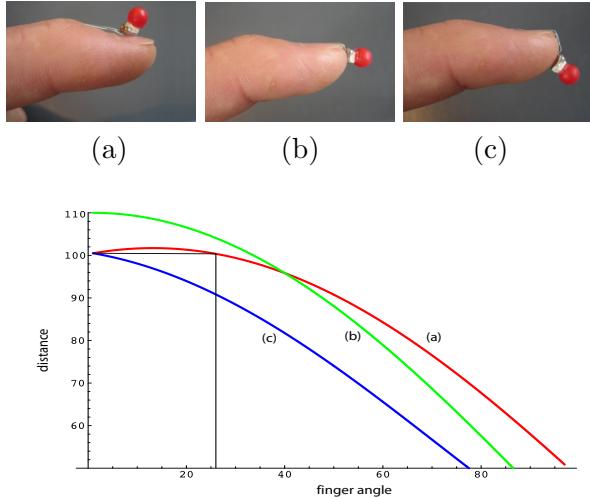


Figure 5: Possible marker positions on the fingertip and influence of the marker position on the distance between base joint and fingertip depending on the finger angle

### 3 User-Specific Calibration

In order to calculate the angles accurately, it is very important to have the exact position of the finger's base joint and the finger length. All procedures of externally measuring such user specific hand geometry have not proved satisfactory. Our approach is to calculate this position from a defined movement of the fingers. The user is required to move up and down the sprawled fingers several times, with the position of the fingertip relative

to the back of the hand being recorded. A circle is fitted to a cloud of measurements [FF99] (cf. fig. 3). Using the known marker position at the tip (fig. 5) the length of the finger can be determined from the radius and the position of the joint relative to the center of the circle.

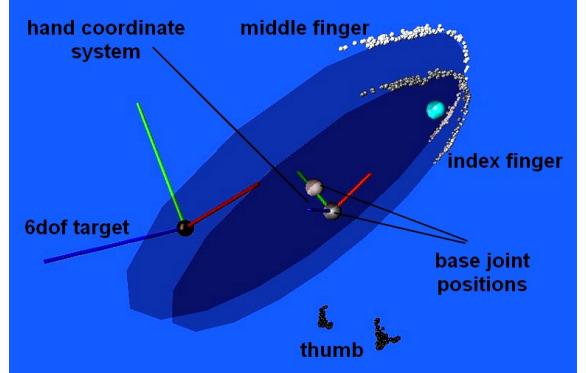


Figure 6: Estimation of the hand coordinate system from measured finger tip locations (left hand)

Additionally, the pose offset between this circle and the target on the back of the hand is used to automatically create a hand coordinate system defined by the hand itself, irrespective of how the user attaches the six degrees of freedom target at the hand.

## 4 Technical Solution

This section shortly describes some technical implementation aspects of our finger-tracking device.

### 4.1 Optical Infrared Tracking

Our device was implemented using a commercially available<sup>1</sup> infrared tracking system. It provides 6 DOF data for the hand target and 3 DOF data for the markers at the fingertips. It is a scalable system with up to 16 cameras. We recommend using at least four cameras for proper detection of arbitrary hand movements.

### 4.2 Merging Markers (Time Division)

One of the general problems of optical marker-based tracking is the danger that several markers can merge into a single blob in an image when they

<sup>1</sup> DTrack by Advanced Realtime Tracking (A.R.T.)

are too close. This is of particular importance for finger tracking since these markers will generally be rather close to one another. We avoid the problem by using a synchronized, sequential addressing scheme for each marker – at the expense of a reduced frame rate.

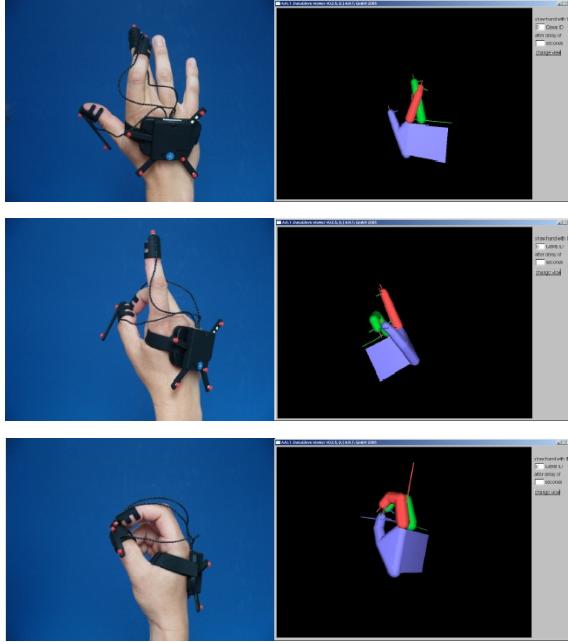


Figure 7: Finger identification in complex situations is possible due to time division multiplexing

### 4.3 Active vs. Passive Markers

There are two possible types of markers for the IR tracking system. Passive (retroreflective) markers do not need any synchronization or power supply. Although the merging problem can be faced by reducing the tracking volume and the marker size, the unique recognition of fingers is difficult with passive markers. It is impossible to detect e.g. crossed fingers.

The second type are active markers. Their main component is an IR emitting LED. To improve the visibility of the LED we added a diffusor sphere (fig. 8(b)). Active markers require a power supply and they need to be synchronized with the tracking system. Yet, they can face the main disadvantages of passive markers.

Using time division multiplexed addressing of active markers reduces the merging problem as well as it makes the marker to finger assignment well-defined (fig.7). The device contains a IR receiver

and a micro-controller to automatically determine the frame rate of the tracking system and provide the time multiplexed marker addressing of the finger markers. The integrated rechargeable battery lasts for 5 to 20 hours of use depending on the selected brightness of the active markers.

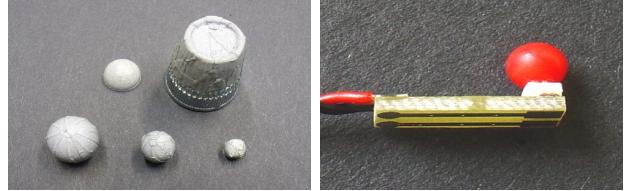


Figure 8: Passive retroreflective markers (a) and active infrared marker with diffusor (b)

## 5 Conclusion & Future Research

Our device has shown that this new approach to determine the fingers' poses is practical for VR applications. Although the absolute accuracy would also be suitable for AR applications, the markers at the fingertips can hinder interactions with real objects. Furthermore, external forces on the fingers may result in finger poses that do not properly fit the assumptions made in section 2.2. This aspect will be the focus of our future research to make the device as suitable for AR as it is for VR. Two calibration aspects have not been considered yet. The first is how to exactly determine the user specific position of the marker at the outermost phalanx. In this work we considered that offset to be given by the finger thimble hardware. The second aspect is the diameter of the fingertip which is approximated during the calibration process. Since these values directly affect the accuracy for collision detection, it is worth thinking about an extra calibration routine for them.

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Figure 9: The finger tracking device in action

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