Position Tracking for Virtual Reality Using Commodity WiFi

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VR today
VR today

User movement

What user sees in the headset
VR today

User movement

What user sees in headset
Infrastructure-free
Infrastructure-free, unrestrained
Current VR experience: Either Cumbersome or Low-fidelity
Current VR experience: complex
WiCapture

No dedicated infrastructure
Room-level range
Occlusion-resistant
WiCapture in action: Comparison with Oculus

Setup

A WiFi chip is attached to a Oculus DK2 VR headset
For tracking the headset, Oculus needs this IR camera within 1-2 meters.
Comparison with Oculus

Setup

WiFi access points required for WiCapture are placed at corners of the room
Comparison with Oculus

Bottom right video shows the actual headset movement
Comparison with Oculus

Top right video shows the trajectory estimated using WiFi
Comparison with Oculus

Top left video shows the trajectory estimated by Oculus system
Comparison with Oculus

Result (Comparison with Oculus DK2)

- To track the target above, four WiFi access points placed at corners of 5 m x 6 m room
No field-of-view limitation

Result (Headset out of field-of-view of Oculus DK2 camera)

Setup same as before

IR-Camera

Front IR-LEDs

WiFi array at target
Result (Headset out of field-of-view of Oculus DK2 camera)

Setup same as before

No field-of-view limitation
Result (Headset’s front occluded from the Oculus DK2 camera)

Setup is different as LEDs face away

Headset turned away from camera
Headset turned away from camera
WiFi as a ToF camera

Reference signal
\[ e^{j2\pi ft} \]

Received signal
\[ e^{j2\pi ft} e^{-j2\pi f\text{ToF}} \]

ToF camera Image
\[
\int \left( e^{j2\pi ft} e^{-i2\pi f t \text{ToF}} \right) e^{-j2\pi ft} dt
\]

= \[ e^{-j2\pi f\text{ToF}} \]
WiFi as a ToF camera

Reference signal: $e^{j2\pi ft}$

Received signal: $e^{j2\pi ft} e^{-j2\pi fToF}$

WiFi CSI Image:

$$= \int \left( e^{j2\pi ft} e^{-i2\pi fToF} \right) e^{-j2\pi ft - j\psi} \, dt$$

$$= e^{-j2\pi fToF - j\psi}$$
Motion creates phase change.

ToF = distance/speed of light
Motion creates phase change

\[ \text{Phase} = \text{ToF} \times (2\pi \times \text{WiFi frequency}) \]

\[ \text{ToF} = \frac{||\vec{\delta}||}{c} \]
Challenge 1: Multipath

ToF of path 1 is $\vec{r}_1 \cdot \hat{\delta} / c$

ToF of path 2 is $\vec{r}_2 \cdot \hat{\delta} / c$
Challenge 1: Multipath

ToF of path 1 is $r_1 \cdot \frac{\delta}{c}$

ToF of path 2 is $r_2 \cdot \frac{\delta}{c}$

Equivalent ToF of overall received signal

Overall received signal

$$\alpha e^{j2\pi f \tau_{eq}} = e^{j2\pi f r_1 \cdot \frac{\delta}{c}} + e^{j2\pi f r_2 \cdot \frac{\delta}{c}}$$
Multipath distorts ToF values
Challenge 2: Different clocks

\[ \int (e^{j2\pi ft} e^{-j2\pi f \text{ToF}}) e^{-j2\pi ft} dt = e^{-j2\pi f \text{ToF}} \]

WiFi-light source

ToF camera

\[ \int (e^{j2\pi ft} e^{-j2\pi f \text{ToF}}) e^{-j2\pi ft - j\psi} dt = e^{-j2\pi f \text{ToF} - j\psi} \]

WiFi receiver
Challenge 2: Different clocks

- Transmitter clock
- Receiver clock

First transmission

Second transmission
Challenge 2: Different clocks

Equivalent ToF of overall received signal

Overall perceived ToF = $\tau_{eq}(t) + o(t)$

Clock offset

$e^{j2\pi f \tau_{per}} = e^{j2\pi f o(t)} e^{j2\pi f \tau_{eq}(t)}$

$= e^{j2\pi f o(t)} [e^{j2\pi f \vec{r}_1 \cdot \vec{\delta}(t)/c} + e^{j2\pi f \vec{r}_2 \cdot \vec{\delta}(t)/c}]$
Clock drift for typical WiFi clocks is 1000 X more than ToF change due to typical motion
Infer

ToF of path 1

from

Overall perceived ToF

Goal
Consider a path. Let's plot ToF of the signal from the path at different antennas.
Solving multipath: Use multiple antennas
Solving multipath: Use multiple antennas

\[ \vec{r}, \vec{d}, \vec{\#} \]

\[ \frac{\vec{r} \cdot \vec{d}}{c} \]

- Antenna 1
- Antenna 2
- Antenna 3
Solving multipath: Use multiple antennas

\[ \frac{(\vec{r} \cdot 2\vec{d})}{c} \]

Equal Distance Line
Modeling signal in terms of multipath

Consider the two paths as before
Modeling signal in terms of multipath

For the first path, ToF at the three antennas

\[
\begin{bmatrix}
\tau_1 \\
\tau_1 + (r_1 \cdot \hat{d})/c \\
\tau_1 + (2r_1 \cdot \hat{d})/c
\end{bmatrix}
\]
Modeling signal in terms of multipath

For the first path, signal at the three antennas

\[
\begin{bmatrix}
e^{-j2\pi f \tau_1} \\
e^{-j2\pi f \tau_1} e^{-j2\pi f (\vec{r}_1 \cdot \hat{d})/c} \\
e^{-j2\pi f \tau_1} e^{-j2\pi f (2\vec{r}_1 \cdot \hat{d})/c}
\end{bmatrix}
\]
Modeling signal in terms of multipath

Combining the signal from both the paths, signal at the three antennas

\[
\begin{align*}
& e^{-j2\pi f \tau_1} + e^{-j2\pi f \tau_2} \\
& e^{-j2\pi f \tau_1} e^{-j2\pi f (\bar{r}_1 \cdot \hat{d})/c} + e^{-j2\pi f \tau_2} e^{-j2\pi f (\bar{r}_2 \cdot \hat{d})/c} \\
& e^{-j2\pi f \tau_1} e^{-j2\pi f (2\bar{r}_1 \cdot \hat{d})/c} + e^{-j2\pi f \tau_2} e^{-j2\pi f (2\bar{r}_2 \cdot \hat{d})/c}
\end{align*}
\]
Modeling signal in terms of multipath

Combining the signal from both the paths, signal at the three antennas

\[
\begin{bmatrix}
1 & 1 \\
1 & 1 \\
\end{bmatrix}
\begin{bmatrix}
e^{-j2\pi f (\vec{r}_1 \cdot \hat{d})/c} & e^{-j2\pi f (\vec{r}_2 \cdot \hat{d})/c} \\
e^{-j2\pi f (2\vec{r}_1 \cdot \hat{d})/c} & e^{-j2\pi f (2\vec{r}_2 \cdot \hat{d})/c} \\
\end{bmatrix}
\begin{bmatrix}
e^{-j2\pi f \tau_1} \\
e^{-j2\pi f \tau_2} \\
\end{bmatrix}
\]
Modeling signal in terms of multipath

As the headset moves, the weights in the linear combination change

\[
\begin{bmatrix}
1 & 1 \\
\exp(-2\pi f (\vec{r}_1 \cdot \hat{d})/c) & \exp(-2\pi f (\vec{r}_2 \cdot \hat{d})/c) \\
\exp(-2\pi f (\vec{r}_1 \cdot \hat{d})/c) & \exp(-2\pi f (\vec{r}_2 \cdot \hat{d})/c)
\end{bmatrix}
\]

\[
\begin{bmatrix}
\exp(-2\pi f \tau_1(t)) \\
\exp(-2\pi f \tau_2(t))
\end{bmatrix}
\]
Modeling signal in terms of multipath

As the headset moves, the weights in the linear combination change

\[
\begin{bmatrix}
1 & 1 \\
\text{e}^{-2\pi f (\hat{r}_1 \cdot \hat{d})/c} & \text{e}^{-2\pi f (\hat{r}_2 \cdot \hat{d})/c} \\
\text{e}^{-2\pi f (2\hat{r}_1 \cdot \hat{d})/c} & \text{e}^{-2\pi f (2\hat{r}_2 \cdot \hat{d})/c}
\end{bmatrix}
\]

One can use standard MUSIC algorithm to recover vectors and weights from multiple linear combinations of the same vectors.
Modeling signal in terms of multipath

As the headset moves, the weights in the linear combination change

\[
\begin{bmatrix}
1 & 1 \\
e^{-2\pi f (\vec{r}_1 \cdot \hat{d})/c} & e^{-2\pi f (\vec{r}_2 \cdot \hat{d})/c} \\
e^{-2\pi f (2\vec{r}_1 \cdot \hat{d})/c} & e^{-2\pi f (2\vec{r}_2 \cdot \hat{d})/c}
\end{bmatrix}
\begin{bmatrix}
e^{-2\pi f \tau_1(t)} \\
e^{-2\pi f \tau_2(t)}
\end{bmatrix}
\]

So, we now have access to $\vec{r}_1$, $\vec{r}_2$, $\tau_1(t)$, and $\tau_2(t)$
We now know the directions of both the paths $\vec{r}_1$ and $\vec{r}_2$
And we know time-series of ToF of both the paths \( \tau_1(t) \) and \( \tau_2(t) \)

\[
\tau_1(t) = \frac{\vec{r}_1 \cdot \delta(t)}{c} + o(t)
\]

\[
\tau_2(t) = \frac{\vec{r}_2 \cdot \delta(t)}{c} + o(t)
\]

\[
e^{j2\pi f \tau_{\text{per}}} = e^{j2\pi f o(t)} \left[ e^{j2\pi f \vec{r}_1 \cdot \delta(t)/c} + e^{j2\pi f \vec{r}_2 \cdot \delta(t)/c} \right]
\]

\[
= [ e^{j2\pi f \left( o(t) + \frac{\vec{r}_1}{c} \delta(t) \right)} + e^{j2\pi f \left( o(t) + \frac{\vec{r}_2}{c} \delta(t) \right)} ]
\]

\[
= [ e^{j2\pi f \tau_1(t)} + e^{j2\pi f \tau_2(t)} ]
\]
\[ \tau_1(t) = \frac{\vec{r}_1 \cdot \ddot{\delta}(t)}{c} + o(t) \]

\[ \tau_2(t) = \frac{\vec{r}_2 \cdot \ddot{\delta}(t)}{c} + o(t) \]

Problematic term is the same
Solving clock offset: Use multipath

Effect of the clock drift is the same for ToF obtained on both the paths.
Solving clock offset: Use multipath

Difference in ToF of the paths

\[ \tau_2(t) - \tau_1(t) \]

\[ = \frac{\vec{r}_2 \cdot \dot{\delta}(t)}{c} + o(t) - \frac{\vec{r}_1 \cdot \dot{\delta}(t)}{c} + o(t) \]

\[ = (\vec{r}_2 - \vec{r}_1) \cdot \ddot{\delta}(t)/c \]

We know the directions of the paths \( \vec{r}_1 \) and \( \vec{r}_2 \), and speed of light \( c \). So, we can recover required \( \ddot{\delta}(t) \)
Evaluation
Mechanical stage experiments

Precision = 0.25 mm
Accuracy = 1.5 mm
Indoor office deployment
Indoor office deployment
Occlusion deployment

1.51 cm
Conclusion

- WiCapture – works with commercial WiFi chips
- Occlusion-resistant, room-level range, insensitive to illumination level and texture
- Potentially enable VR on mobile
INPUT:
270 complex numbers (3 tx antennas X 3 rx antennas X 30 frequencies)

Neural network (3 layers)

OUTPUT:
Position (x,y,z)

Collected millions of data-points from 90 different locations throughout Stanford campus. Neural network has larger error of 2 cm for two-dimensional data. Neural network is very fast with python implementation on a Macbook taking only 25 ms. NOT YET PUBLISHED
Solving multipath:
Use multiple antennas
Solving multipath: Use multiple antennas
Useful slides
Equivalent ToF of overall received signal

$\tau_{eq}$

Time

$\tau_{per}$
ToF = distance/speed of light
ToF = distance/speed of light
ToF of path 1

Time
ToF of path 1
ToF of path 1

ToF\textsubscript{1}

Time

ToF of path 2

ToF\textsubscript{2}

Time
Challenge 1: Multipath

ToF of path 1

ToF of path 2

Time