AirCode: Unobtrusive Physical Tags for Digital Fabrication

Dingzeyu Li
Avinash S. Nair
Shree K. Nayar
Changxi Zheng
Tags are everywhere.

Tags alter appearance.

metadata
hyperlink
interaction

luggage tags
boarding passes
product barcodes
mailing labels
Compromises on Aesthetics
Unobtrusive Tagging for Fabrication
Related Work

InfraStructs - Terahertz [Willis et al., SIGGRAPH 2013]

Acoustic Barcodes [Harrison et al., UIST 2012]

Affordance++ - Stimulating [Lopes et al., CHI 2015]
Light Transport
Light Transport

light → direct → camera
Light Transport

- Light
- Subsurface scattering
- Camera

Global light transport involves the interaction of light with a surface, including subsurface scattering, before reaching the camera.
Combined

light → direct ≈ global → camera
Combined

light  direct  global  camera
idea: embed unobtrusive tags in the global component

1. How to guarantee the tags are invisible?
2. How to detect the global component?
Separate Global Component

[Nayar et al., SIGGRAPH 2006]
Separate Global Component

[Nayar et al., SIGGRAPH 2006]
Air Pockets

projector

direct

camera

air
Air Pockets

- Projector
- Global
- Subsurface scattering
- Camera
Air Pockets

- Direct
- Global

Intensity vs Position

Subsurface Scattering
Air Pockets

direct  global

subsurface scattering
AirCode Layout

- Markers
- Data Bits
- Calibration Bits
AirCode Benefits

- during fabrication
- invisible
- camera/projector setup
Contrast threshold is the minimal contrast required to see the target reliably.
Invisibility: Contrast Threshold

Contrast threshold is the minimal contrast required to see the target reliably.

\[
\text{contrast} = \frac{L_{\text{max}} - L_{\text{min}}}{\bar{L}}
\]

0.1% - 10%

[Campbell and Robson, Journal of Physiology 1968]
[Bijl et al., Vision Research 1989]
Layered Scattering Model

Reflection profile \( R(d) \)

Transmission profile \( T(d) \)

- multi-layer reflection profile

[Donner and Jensen, SIGGRAPH 2005]
Multi-Layer Profile

\[ R(d) = R_1 + T_1 R_2 T_1 + T_1 R_2 R_1 R_2 T_1 + \cdots \]

0-bounce 1-bounce 2-bounce

\[ = R_1 + T_1 R_2 T_1 (1 + R_1 R_2 + (R_1 R_2)^2 + \cdots) \]

\[ = R_1 + \frac{T_1 R_2 T_1}{1 - R_1 R_2} \]

Efficient computation for layered material

[Donner and Jensen, SIGGRAPH 2005]
Putting it together

\[ R(d) = R_1 + T_1 R_2 T_1 + T_1 R_2 R_1 R_2 T_1 + \cdots + 0.1\% - 10\% \]

Details in the paper
Applications

- metadata embedding
- robotic grasping
- paper watermarking
Metadata Embedding
Metadata Embedding

direct

global

“visibility”
Physical Hyperlink
Moai

Moai (mōˈē), or moaia, are monolithic human figures carved by the Rapa Nui people on Easter Island in eastern Polynesia between the years 1250 and 1500. Nearly half are still at Rano Raraku, the main moai quarry, but hundreds were transported from there and set on stone platforms called ahu around the island’s perimeter. Almost all moai have overly large heads three-eighths the size of the whole statue. The moai are chiefly the living faces (manga ora) of dead ancestors (manga ariki); the statues’ still gazed inland across their clan lands when Europeans first visited the island in 1722, but all of them had fallen by the latter part of the 19th century.

This article is about the monolithic statues of Easter Island. For other uses, see Moai (disambiguation).
Robotic Grasping

recognition - pose estimation - gasping location
Beyond 3D Printing Materials
Paper Watermarking

Can you see the text?
Can you see the text?

Yes!

global component
Air Pockets in Paper
Separation Results

**imperceptible**
*adjective*
impossible to perceive.

**subsurface**
*adjective*
located beneath a surface.

**code**
*noun*
a system of words, letters, figures, or other symbols substituted for other words, letters, etc., especially for the purposes of secrecy.

**direct**

**imperceptible**
*adjective*
impossible to perceive.

**subsurface**
*adjective*
located beneath a surface.

**code**
*noun*
a system of words, letters, figures, or other symbols substituted for other words, letters, etc., especially for the purposes of secrecy.

**global**
Separation Results

imperceptible
adjective
impossible to perceive.

subsurface
adjective
located beneath a surface.

code
noun
a system of words, letters, figures, or other symbols substituted for other words, letters, etc., especially for the purposes of secrecy.

mask
global
imperceptible adjective
impossible to perceive.

subsurface adjective
located beneath a surface.

code noun
a system of words, letters, figures, or other symbols substituted for other words, letters, etc., especially for the purposes of secrecy.

mask

filtered global
Conclusion

AirCode to Tag Physical Objects
embedded during fabrication
unobtrusive
robust decoding with camera/projector
non-opaque material

Limitations and Future Work
capture time
non-smooth surface
long-term preservation
changeability
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