Legible Robot Pointing

Rachel Holladay
Anca Dragan
Siddhartha Srinivasa
How can a robot autonomously generate legible pointing configurations?
Ray Model for Pointing
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\[ \mathcal{P} \]
Ray Model for Pointing

\[ R_G(P) = \int dr \]
Ray Model for Pointing

\[ R_G(P) = \int \delta(P, r, G) \, dr \]
Ray Model for Pointing

\[ R_G(P) = \int \delta(P, r, G) w(r) \, dr \]
Ray Model for Pointing

\[ R_G(P) = \frac{\int \delta(P, r, G) w(r) \, dr}{\int w(r) \, dr} \]
The Cost of a Pointer

\[ C_G (P) \]
The Cost of a Pointer

\[ C_G(P) = (1 - R_G(P)) \]

Maximize \( R_G \)
The Cost of a Pointer

\[ C_G(P) = (1 - R_G(P)) + \frac{\lambda}{M} ||S - P||^2 \]

Maximize \( R_G \)  
Minimize Distance
\[ C_G(P) = (1 - R_G(P)) + \frac{\lambda}{M} ||S - P||^2 \]
The Cost of a Pointer

\[ C_G(P) = (1 - R_G(P)) + \frac{\lambda}{M} ||S - P||^2 \]
Key Insight:
Consider what you are pointing at and what you aren’t pointing at.
Model for Legible Pointing
Model for Legible Pointing

\[ p(P | G) \propto e^{-c_{G}(P)} \]
Model for Legible Pointing

\[ p(P|G) \implies p(G|P) \]

\[ p(P_i | G) \]
Model for Legible Pointing

\[ p(G_{\text{red}} \mid P) \quad p(G_{\text{green}} \mid P) \]
Model for Legible Pointing

\[ L_G(P) = P(G|P) \]
Model for Legible Pointing

\[ p^* = \max_{p \in P} L_G(p) \]

\[ p(G_{red} \mid P) \quad p(G_{green} \mid P) \]
Model for Legible Pointing

\[ p^* = \max_{p \in P} L_G(p) \]

\[ p \leftarrow p + \alpha \nabla L_G \]
Legible Pointing :
\[ C_G \neq L_G \]
Legible Pointing:

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Legible Pointing:
\[ C_G \neq L_G \]
Legible Pointing:
\[ R_G \neq L_G \]
Legible Pointing:

\[ R_G \neq L_G \]
Legible Pointing:
\[ R_G \neq L_G \]
Legible Pointing:

\[ R_G \neq L_G \]
Legible Pointing : Orientation
Legible Pointing : Orientation
Exaggerate to increase legibility
Does it work?
$C_G \neq L_G$
[Position]

Follow-Up #1:
$R_G \neq L_G$
[Position]

Follow-Up #2:
$C_G \neq L_G$
[Orientation]
Does it work?

$C_G \neq L_G$

[Position]

Follow-Up #1:

$R_G \neq L_G$

[Position]

Follow-Up #2:

$C_G \neq L_G$

[Orientation]
Theoretical $L_G$ affects legibility in practice.
Measuring Legibility

Objective Measure: accuracy

○ Left ○ Right

Subjective Measure: rating

confidence

○ ○ ○ ○ ○ ○ ○ ○

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Between-Subjects Study (N=80)

Manipulate:

\[
\begin{align*}
C_G & \quad L_G \\
\text{model} & \\
\end{align*}
\]

Measure:

legibility: (accuracy + confidence)
Between-Subjects Study (N=80)
Between-Subjects Study \((N=80)\)
Does it work?

Follow-Up #1:

\[ C_G \neq L_G \]
[Position]

Follow-Up #2:

\[ R_G \neq L_G \]
[Position]

[Orientation]
The ray model alone does not produce legible pointing.
Legible Pointing:
Difference from the Ray Model
Within-Subjects Study \((N=20)\)
Within-Subjects Study \((N=20)\)

The ray model alone is not sufficient for legibility.
Does it work?
\[ C_G \neq L_G \]  [Position]

Follow-Up #1:
\[ R_G \neq L_G \]  [Position]

Follow-Up #2:
\[ C_G \neq L_G \]  [Orientation]
Angle exaggeration increases legibility.
Within-Subjects Study \((N=20)\)
Within-Subjects Study (N=20)

Exaggeration increases legibility
Creating a Legible Pointer

Does is work?

\[ C_G \neq L_G \]  
[Position]

Follow-Up #1:

\[ R_G \neq L_G \]  
[Position]

Follow-Up #2:

\[ C_G \neq L_G \]  
[Orientation]
What’s next?
Point of View
Gesture Sequence

Stoke/Hold

Gesture Sequence

Preparation/Begin


Stroke/Hold

Retraction/End
Multi-Object Planning
Gaze

[Admoni 2014]
Key Insight: Pointing is not just about pointing to the correct object, but also about NOT pointing at the other objects.
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https://personalrobotics.ri.cmu.edu/