Dynamic Footprint-based Person Recognition Method and Application to Intelligent Residential Space

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Contents

I. Introduction

II. Literature Review: Gait vs. Footprint
   1. Gait vs. Footprint
   2. Problem Statement

III. Dynamic Footprint
   1. Definition of dynamic footprint
   2. Measurement of dynamic footprint
   3. Footprint database using MAT sensor (MAT-DB)

IV. Dynamic Footprint-based User Identification System
   1. User Identification Method via Overlapped Footprint Shape
   2. User Identification Method via COP Trajectory
   3. Information fusion

V. Concluding Remarks
I. Introduction
Personalized Service: A veteran waitress in a restaurant

Observation ↔ Modeling

Customer’s Behaviors

Left-handed or Right-handed
A Person comes in the GAP store.
The system tells him with his biometrics and his previous purchase data as follows:
- Hello, Mr. Yakamodo.
- Welcome back to the GAP.
- How was the tank-tops of GAP for you?
Motivation: Personalized service

Realize a personalized service for multi-user living environment by human-friendly user identification method!
Historical Trends of User Identification

- “something that you possess”
  - Lost, stolen, forgotten, misplaced, or abused
  
  **To enhance security**

- “something that you know” & “something that you possess”
  - Difficult to remember, easily recallable password
  
  **To enhance convenience**
  (human-friendliness)

- “something that you are” (biometrics)
  - Cannot be misplaced or forgotten

---

Remark: What is biometrics?

- A science involving the statistical analysis of biological characteristics (wide-sense)

- The automated method of physiological or behavioral characteristics to determine or verify identity (narrow-sense)
  - Universality
  - Uniqueness
  - Permanence
  - Collectability
  - Performance
  - Acceptability (Human-friendliness)
  - Circumvention

## Comparison of biometrics

<table>
<thead>
<tr>
<th>Biometrics</th>
<th>Characteristic</th>
<th>Universality</th>
<th>Uniqueness</th>
<th>Permanence</th>
<th>Collectability</th>
<th>Performance</th>
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<td>0</td>
<td>1</td>
<td>0.5</td>
</tr>
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</table>

1: High, 0.5: Medium, 0: Low

Physiological vs. Behavioral

Note: behavioral/physiological distinction is slightly artificial.
An important characteristic is that behavioral biometrics has time series data.

Behavorial biometrics

Introduction

Gait information is one of the most appropriate method for the general living environment including futuristic home environment!

II. Literature Review and Problem Statement

II-1. Gait vs. Footprint
II-2. Problem Statement
Gait as “a total walking cycle”

- M. P. Murray et al. (1967) suggests that gait could be considered as a total walking cycle (periodic) and, if all gait movements were considered, gait is unique.

- Recent research trends on gait recognition

**Model-based approach [Jain 1999]**

**Template-based approach [Huang 1999]**


**Issues in gait recognition: different speed**

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<tr>
<th>Report</th>
<th>Num. of person</th>
<th>Recog. rate of walking person</th>
<th>Recog. Rate of running person</th>
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<tr>
<td>[Yam 2001]</td>
<td>5</td>
<td>96%</td>
<td>92%</td>
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<tr>
<td>[Yam 2002]</td>
<td>20</td>
<td>84.2%</td>
<td>91.7%</td>
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</tbody>
</table>


Issues in gait recognition: different viewing direction

方向 | 人数 | 识别率
--- | --- | ---
前额平行 | 41 | 47%
非前额平行 | 17 | 65%

Issues in gait recognition: Low performance

- Multi-modal biometrics

Face + Gait

Using multiple views

Age, gender, race, shoes and age at which wearing shoes begins

Different foot shape

Human footprint as a biometrics

- R. B. Kennedy suggests that footprint is unique in each person by comparing 38 measurements from 3000 people’s 6000 inked barefoot impression data.
- With 5mm margin, there was no same foot.

Footprint feature used by Kennedy’s work

Automated footprint recognition

- K. Nakajima suggests the first version of automated footprint recognition system based on template matching, COP distance and foot angle.

Assumption: Same body posture at every measurement time

Result: 85% (10 men, 10 training images per individual)

Features used by Nakajima

Normalized foot for template matching

Human footprint as a biometrics

Kennedy’s work (1996)

• R. B. Kennedy suggests that footprint is unique in each person by comparing 38 measurements from 3000 people’s 6000 inked barefoot impression data.

• Result: , no same foot with 5mm margin (3000 people)

Nakajima’s work (2001)

• K. Nakajima suggests the first version of automated footprint recognition system based on template matching, COP distance and foot angle.

• Result: 86.55 % (10 men, 11 training images per individual)


Comparison of Kennedy’s and Nakajima’s work: spatial resolution

Kennedy’s data

Nakajima’s data
Sensor size = 10 x 10 mm²
Literature Review: Gait vs. Footprint

Comparison: overlapped footprint during walking vs. standing footprint

**Kennedy’s work**

- Footprints were taken under controller conditions ensuring that each person steps onto the paper in the same manner.

**Nakajima’s work**

- Footprints were taken under controller conditions ensuring that each person stood straight at the center of mat and looked toward a mark on the wall. And then averaging data during 5 sec.
Literature Review: Gait vs. Footprint

Comparison: local feature vs. global feature (template matching)

Kennedy’s work

Nakajima’s work
## Problem Statement

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td><strong>Recognition Result</strong></td>
<td><strong>Measurement Device</strong></td>
</tr>
<tr>
<td>86.55% (10 person, 11 samples)</td>
<td>Pressure sensing mat</td>
</tr>
<tr>
<td>84.2% (walking) 91.7% (running) (20 person, 6 samples)</td>
<td>Vision (lateral-view)</td>
</tr>
</tbody>
</table>

**Fusion of footprint and gait information**


Dynamic Footprint-based User Identification System – 26/59
“Given N person’s sequential walking footprints and a new sequential walking footprint M, find the person whose walking footprint is most similar to the walking footprint M.”

Sequential walking footprint (my idea!)

= 2D projected data of 3D human gait

= \{ Dynamic information (gait)
   Static information (foot shape) \}

∋ \{ COP/COA trajectory
   Overlapped footprint \}

Human walking  ➔  Sequential walking footprint (dynamic footprint)  ➔  COP trajectory

Foot shape

Dynamic Footprint-based User Identification System–27/59
III. Dynamic Footprint

III-1. Definition of dynamic footprint
III-2. Measurement of dynamic footprint
III-3. Footprint database using MAT sensor
Characteristics of sequential footprints from human walking

I. Repeatability

“Gait could be considered as a periodic walking cycle.” [Jain 1999]
Footprints during walking are 2D projected information of human gait. Therefore, footprints during walking also have a repeatability.

II. Asymmetry

“The shape of the left foot is typically different from that of the right foot.” [Sforza 1998]
Footprint patterns of each foot during walking are also asymmetric.

Definition of dynamic footprint

For \( K=0, 1, \cdots, T-1 \), \( F_K : [0 \leq x \leq W_x, 0 \leq y \leq W_y] \rightarrow [0 \leq p \leq P_{\text{max}}] \) (\( W_x/W_y \): spatial width/height of sensor, \( P_{\text{max}} \): normalized max. pressure value)

A (discrete-)time sequence of footprint images \( F_K, K=0, 1, \cdots, T-1 \) is called a dynamic footprint if the following conditions are satisfied:

1) \( \exists \ m \in \mathbb{N} \) s. t. \( F_K \approx F_{m+K} \) for \( \forall K=0, \cdots, T-1 \)
   
   ("A \approx B" means A=R(T(B)) for some rotation R and Translation T)

2) \( F_0 \) is the image at the right or left heel contact time in a single gait cycle.
Definition of dynamic footprint

For $K=0, 1, \cdots, T-1$, \( F_k : [0 \leq x \leq W_x, 0 \leq y \leq W_y] \rightarrow [0 \leq p \leq P_{\text{max}}] \)

\( (W_x/W_y: \text{spatial width/height of sensor, } P_{\text{max}}: \text{normalized max. pressure value}) \)

Overlapped Footprint (Shape): \( F(x, y) = \begin{cases} 
1 & \text{if } \bigcup_{K=0}^{T-1} F_k(x, y) \geq P_{\text{threshold}} \\
0 & \text{otherwise}
\end{cases} \)

where \( P_{\text{threshold}} \) is the threshold for noise elimination

Center-Of-Pressure Point in \( F_k \): \( \text{COP}_k = (x_k^*, y_k^*) \)

\[ x_k^* = \frac{\sum_x \sum_y x F_K(x, y)}{\sum_{x,y} F_K(x, y)} , \quad y_k^* = \frac{\sum_y \sum_x y F_K(x, y)}{\sum_{x,y} F_K(x, y)} \]

Center-Of-Pressure Trajectory: \( \text{COPT} = \{ \text{COP}_0, \text{COP}_1, \text{COP}_2, \ldots, \text{COP}_{T-1} \} \)
Measurement of dynamic footprint

<table>
<thead>
<tr>
<th>Location of sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAT sensor</td>
</tr>
<tr>
<td>Shoe sensor</td>
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<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Pressure Sensor</th>
<th>Temperature Sensor</th>
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<tbody>
<tr>
<td>MAT sensor</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Easy</td>
<td>Difficult</td>
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<tr>
<td>Shoe sensor</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Difficult</td>
<td>Easy</td>
</tr>
</tbody>
</table>

**Mat-type pressure sensor**


Dynamic Footprint-based User Identification System—32/59
**Assumptions on measurement**

(A-1) There is no other object on the MAT sensor except the walking person.

(A-2) There is only one walking person on the MAT sensor in each trial.

To find the starting time of dynamic footprint

(A-3) During one’s walking on the MAT sensor, at least one element of the MAT sensor is fired.

To find the ending time of dynamic footprint

(A-4) Normally, user always walks along the designated direction (for example, outdoor-to-indoor) on the MAT sensor.

To exclude the change of walking direction
Assumptions on measurement (cont’d)

(A-5) User’s step length (the distance between the COA point of the first foot and that of the second foot) is greater than a predefined maximum foot length, $L_{MAX\_FOOT}$

- To discriminate the first foot and second foot parts

(A-6) The ‘two’ footprints are always acquired after a single gait cycle.

- To exclude the imperfect footprint

(A-7) The user has to walk on the MAT sensor without wearing any shoes (that is, barefoot walking is assumed).

- To exclude the effect of the sole of shoes
Assumptions on walking person

(A-8) The person who may sometimes drag their foot after another is excluded from the subjects.

To exclude abnormally walking users
( users with foot pain)

(A-9) Users are in normal mood when they walk.

To exclude the emotional effect

(A-10) Users have not any additional loading weight except their body and clothes.

To exclude the effect of weight loading
Footprint database, MAT-DB

*Footprint DB using mat-type sensor*

- Number of person = 11 (M:9, F:2)
- Number of data per each person = 40
- Period of data gathering = 40 days
- Contents of data = dynamic footprint
- Sensor = FOOT ANALZER
- Frame rate = 30 Hz

**FOOT ANALZER** (TechStorm, Inc.)

- Total size: 400 x 800 mm²
- Spatial resolution: 10 x 10 mm
- Number of sensors: 40 x 80
- Max. sampling speed = 30 Hz
- FSR-based mat-type pressure sensor
IV. Dynamic Footprint-based User Identification System

IV-1. User Identification Method via Overlapped Footprint Shape
IV-2. User Identification Method via Center-Of-Pressure Trajectory
IV-3. Information fusion
Person Recognition Method via Overlapped Footprint Shape

Feature Extraction

Walking Footprint → Overlapped Footprint Shape Extraction

User Identification

Footprint Shape Matching (Type I) → Degrees of Shape Dissimilarity → User ID

Overlapped Footprint Shape

Dynamic Footprint-based User Identification System–38/59
Overlapped Footprint Shapes
Person Recognition Method via Overlapped Footprint Shape

[Procedures for extracting aligned footprint]

When a dynamic footprint $F^*(x, y)$ is given,

Step 1. Labeling of each blob
Step 2. Finding COA points of each blob
Step 3. Determine first foot / second foot
Step 4. Updating overlapped footprint image
Step 5. Creation of overlapped footprint image
Step 6. Finding the rotation angle using the principal axes of overlapped footprint image
Step 7. Creation of aligned footprint, $\hat{F}^*(x, y)$
Person Recognition Method via Overlapped Footprint Shape

[User Identification Method]

When a dynamic footprint $F^*(x,y)$ and $F^i(x,y), i = 1,..,U$ are given, (Num. of User = U)

[Type I: Dissimilarity]

User ID $i^* = \arg\min_i \sqrt{\sum_{x,y} (F^*(x,y) - F^i(x,y))^2}

Deg. of Dissimilarity = $\sqrt{\sum_{x,y} (F^*(x,y) - F^{i*}(x,y))^2}$

Considering the foot size

[Type II. Similarity]

User ID $i^* = \arg\max_i \frac{P(F^* \cap F^i)}{\sqrt{P(F^*)P(F^i)}}

Deg. of Dissimilarity = $\frac{P(F^* \cap F^{i*})}{\sqrt{P(F^*)P(F^{i*})}}$

Considering the normalization

where P(A) is total number of pixels which has bigger value than threshold value
Person Recognition Method via Overlapped Footprint Shape

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<th>Nakajima method</th>
<th>Method for normalization</th>
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</table>

Given two images A and B,

Nakajima method (Type I)

\[
\text{Dissimilarity value} = \sqrt{\sum_{x,y} \{I_A(x,y) - I_B(x,y)\}^2}
\]

Method for normalization (Type II)

\[
\text{Similarity value} = \frac{P(A \cap B)}{\sqrt{P(A)P(B)}}
\]

where P(A) is total number of pixels which has bigger value than threshold value.
Discussion on dissimilarity value (Type I)

Result with the data of user ID = 1

USER 1

Result with the data of user ID = 2

USER 2

Changing range: 3 pixels

Changing range: 4 pixels

Sensitive to noise
**Person Recognition Method via COP Trajectory**

**Feature Extraction**
- Walking Footprint
- Quantized COPT Extraction

**User Identification**
- Registered HMMs
  - First Foot’s COPT Matching
  - Second Foot’s COPT Matching
- Degrees of COPT Similarity
- weighted sum

**User ID**
COP trajectories (COPTs)
Person Recognition Method via COP Trajectory

[Procedures for extracting aligned footprint]

Step 1. Labeling of each blob
Step 2. Finding COA points of each blob
Step 3. Determine first foot / second foot
Step 4. Check whether current time is the ending time of first foot or the start time of second foot
Step 5. Updating overlapped footprint image
Step 6. Updating COP trajectory of each foot
Step 7. Creation of overlapped footprint image
Step 8. Finding the rotation angle using the principal axes of overlapped footprint image
Step 9. Creation of aligned COP trajectory
Characteristics of COP trajectory

- Varying length time-series data with noise (by quantization)
  - Hidden Markov Model
- Different COP trajectories between Left and right feet
  - Separate model for each foot
- Different curvatures as users
  - Direction-based quantization
    (Relative position-based quantization)
Person Recognition Method via COPT

Center-Of-Pressure Trajectory

Relative position-based quantization

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<td>Δx = 0</td>
<td>0 &lt; Δx ≤ Tx</td>
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<td>Δx = 0</td>
<td>Δx = 0</td>
<td>0 &lt; Δx ≤ Ty</td>
<td>Δx &gt; Ty</td>
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<tr>
<td>0 &lt; Δy ≤ Ty</td>
<td>0 &lt; Δy ≤ Ty</td>
<td>0 &lt; Δy ≤ Ty</td>
<td>0 &lt; Δy ≤ Ty</td>
<td>0 &lt; Δy ≤ Ty</td>
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<tbody>
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<td>Δx &lt; -Ty</td>
<td>Δx = 0</td>
<td>0 &lt; Δx ≤ Tx</td>
<td>Δx &gt; Tx</td>
</tr>
<tr>
<td>Δy &gt; Ty</td>
<td>Δy &gt; Ty</td>
<td>Δy &gt; Ty</td>
<td>Δy &gt; Ty</td>
<td>Δy &gt; Ty</td>
</tr>
</tbody>
</table>

HMM-based footprint recognizer

First foot in one step

Second foot in one step

Prob.

Prob.

Prob.

Prob.

User

Learning by LM method

Name 12... N
Registration of HMMs: Baum-Welch Algorithm

- **Element of HMM**
  - Set of hidden states: \( S = \{S_1, S_2, \ldots, S_N\} \)
    where \( N \) is the number of states in the model.
  
  - State transition probability: \( A = \{a_{ij}\} \) for \( 1 \leq i, j \leq N \)
    where \( a_{ij} = P[q_{t+1} = S_j \mid q_t = S_i] \), \( 0 \leq a_{ij} \), \( \sum a_{ij} = 1 \)
  
  - Set of observation symbols: \( V = \{v_1, v_2, \ldots, v_M\} \)
    where \( M \) is the number of observation symbols per state.
  
  - Observation symbol probability: \( B = \{b_j(k)\} \) for \( 1 \leq j \leq N, 1 \leq k \leq M \)
    where \( b_j(k) = P[v_k \text{ at } t \mid q_t = S_i] \), \( 0 \leq b_j(k) \), \( \sum b_j(k) = 1 \)
  
  - Initial state probability: \( \prod = \{\prod_i\} \), \( 1 \leq i \leq N \)
    Where \( \prod_i = P[q_1 = S_i] \), \( 0 \leq \prod_i \), \( \sum \prod_i = 1 \)

Registration of HMMs: Baum-Welch Algorithm

1) Initialization of HMMs \( \lambda = (A, B, \pi) \) : Equal prob. Dist.

2) Calculation of prob. at each node (state)
\[
\gamma_t(i, j) = p(s_t = i, s_{t+1} = j | O, \lambda) = \frac{\alpha_t(i) a_{ij} b_j(O_{t+1}) \beta_{t+1}(j)}{p(O | \lambda)} = \frac{\alpha_t(i) b_j(O_{t+1}) \beta_{t+1}(j)}{\sum_{l \in S_F} \alpha_T(l)}
\]

3) Re-estimation of model parameters
\[
\hat{a}_{ij} = \frac{\sum_{t=1}^{T-1} \gamma_t(i, j)}{\sum_{t=1}^{T-1} \sum_j \gamma_t(i, j)} \quad \hat{b}_j(k) = \frac{\sum_{t=O_t=v_k} \gamma_t(i)}{\sum_{t=1}^{T} \gamma_t(i)} \quad \hat{\pi} = \gamma_1(i)
\]

4) If \( p(O | \hat{\lambda}) - p(O | \lambda) \leq \varepsilon \), stop. Else, continue to step 2.

Observation evaluation \( p(O | \lambda) = \sum_{i=1}^{N} \alpha_T(i) \)
User Identification Method

Given the prob. $P_i = p(O|\lambda_i)$ from U user’s HMMs $\lambda_i, i=1,...,2U$ (O: quantized COPT)

User ID $j^* = \arg\max_j S_j, \ S_j = \sum_i w_{ij} p(O|\lambda_i)$ Deg. of Similarity = $S_{j^*}$

Error function:

$$\tilde{E} = \frac{1}{2} \left\| \varepsilon (w_{old}) + Z (w_{new} - w_{old}) \right\|^2 + \lambda \left\| w_{new} - w_{old} \right\|^2$$

$$(Z)_{ni} = \frac{\partial \varepsilon^n}{\partial w_i} \text{ where } \varepsilon^n \text{ is the error for } n^{th} \text{ pattern}$$

Weight-updating rule:

$$w_{new} = w_{old} - (Z^T Z + \lambda I)^{-1} Z^T \varepsilon (w_{old})$$

Small $\lambda$: Newton method
Large $\lambda$: Gradient descent method
Used $\lambda$: Adaptive updating with initial value 0.01

[REF] C. M. Bishop, Neural Networks for Pattern Recognition, Oxford University Press Inc., 1995
User identification via COP trajectory

As time goes on,

<table>
<thead>
<tr>
<th># of learning data</th>
<th>FRR</th>
<th>FAR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average (%)</td>
<td>Max. (%)</td>
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<tr>
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<td>93.18</td>
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<td>4</td>
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<tr>
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<tr>
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<tr>
<td>12</td>
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<tr>
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</tr>
<tr>
<td>20</td>
<td>20.45</td>
<td>50.00</td>
</tr>
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</table>
Comparison of foot shape and COPT

Result by overlapped footprint shape

Result with the data of user ID = 1

Min. FRR error = 8.64%
Changing range in dissimilarity = 3 pixels
(Sensitive to noise)

Result by COP trajectory

FRR with different number of learning data

Min. FRR error = 20.45%

Combination of two independent information
Information Fusion

Feature Extraction

Overlapped Footprint Shape Extraction

Quantized COPT Extraction

Walking Footprint

User Identification

Footprint Shape Matching (Type-II)

Degrees of Shape Similarity

First Foot’s COPT Matching

Second Foot’s COPT Matching

 Degrees of COPT Similarity

Registered Footprint Templates

Registered HMMs

Weighted Sum

User ID

Registered Weight

Registered Weight

Dynamic Footprint-based User Identification System–54/59
Unified algorithm for the extraction of aligned overlapped foot shape and COP trajectory

[Procedures for extracting aligned footprint]

- Step 1. Labeling of each blob
- Step 2. Finding COA points of each blob
- Step 3. Determine first foot / second foot
- Step 4. Check whether current time is the ending time of first foot or the start time of second foot
- Step 5. Updating overlapped footprint image
- Step 6. Updating COP trajectory of each foot
- Step 7. Creation of overlapped footprint image
- Step 8. Finding the rotation angle using the principal axes of overlapped footprint image
- Step 9. Creation of aligned footprint
- Step 10. Creation of aligned COP trajectory

Common step
--- Step for foot shape
----- Step for COP trajectory
Result of Information Fusion

Result of the fusion of footprint shape info. & COP trajectory info.

<table>
<thead>
<tr>
<th>User ID</th>
<th>FRR (%)</th>
<th>FAR (%)</th>
</tr>
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<tbody>
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<td>0.00</td>
</tr>
<tr>
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<td>0.00</td>
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<tr>
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<td>0.00</td>
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<tr>
<td>USER 10</td>
<td>5.00</td>
<td>0.00</td>
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<tr>
<td>TOTAL</td>
<td>1.36</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Each person’s test data

Recognition result of a user

Foot Shape + COPT
Foot Shape
COPT

One sample from u1 (user 1) is compared with all other data.

u1 u2 u3 u4 u5 u6 u7 u8 u9 u10 u11
Application Example

Automatic Door-Opening Service System

Walking Rail System

- Example of Personalized Service
- Person Recognition by Overlapped Footprint Shape
- Greeting/Messaging Service
Concluding Remark

1. Analysis of previous footprint-based user identification method

2. Performance enhancement of previous footprint-based user identification method by using the overlapped footprint shape (from 86.55% to 91.36%)

3. Proposal of COP trajectory-based user identification (FRR error = 20.45%)

6. Proposal of multi-modal identification using both aligned overlapped foot shape and aligned COP trajectory

8. Successful fusion of previous gait and footprint method (FRR error = 1.36%)
Thank you for your attention

Dynamic Footprint =

\[ \text{COP trajectory (Gait info.)} + \text{Overlapped footprint shape (Footprint info.)} \]

Transient Response \hspace{2cm} Steady State Response