Humanoid Robotics at Waseda University

Tutorial on Humanoid Technologies
The 2nd EC FP7 RoboSoM Project Meeting
February 18, 2010

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Waseda’s Achievements in Humanoid Robotics led by the late Prof. Ichiro Kato

WABOT-1 (1973)  
Why Humanoid Robotics?

- To Build Human Model to Understand Human from Robotics View Point: “Robotic Human Science”
- To Make Robotics as One of the Social Technologies based on the Human Model to Support Elderly Dominated Society and to Support Education, Etc.
- Grand Challenge for Roboticists: A human is considered to be an extreme robot both in motional functionality and in intelligent functionality.
Humanoid Family in WABOT-HOUSE Project
WABIAN-2 as a Robotic Human Simulator and a Measuring Device for Quantitative Evaluation of Handicapped/Elderly Supporting Machines/Robots

Yu Ogura Team

- height : 1.5 [m]
- weight : 55 [kg]

Total DOF : 41

- leg : 6 × 2
- waist : 2
- trunk : 2
- arm : 7 × 2
- neck : 3

2-DOF Pelvis

2 DOF

3 DOF

1 DOF

3 DOF
New Leg-Body Mechanism Inspired by Human Walking

Modeling of Pelvis Motion

Pelvis-Waist Mechanism: 2DOF

- Stretch walking
- Obstacle avoidance

2 DOF hips
Most Tough Parts in Design:
Waist-Pelvis-Hip-Knee
WABIAN-2 Designed Based on the Human Dimensions
More Human-like Walking by WABIAN-2R with a 50cm-Step

0.50[m/step], 0.96[s/step]
Human-Like Outdoor Walking

0.40[m/step], 0.96[s/step]
Two Peaks in Vertical Floor Reaction Force

垂直床反力（2周期弱）

Knee Extension Walking

Knee Bended Walking

Human Walking
WABIAN-2’s Walking Assisted by Hitachi Walker for Elderly/Handicapped

Bending 0.2[m]  Knee stretched 0.2[m]
Real World Simulations of a human assisted by the Walker
Optimal Pattern
Applications of Waseda’s Bipedal Walking Robot Technology

- METI HRP-1
- ZMP PINO2
- TMSUK/Waseda WL-16
- SONY QRIO
SHINPO「新歩」: A Brother of WABIAN-2
Walking in Niigata Natural Science Museum Resulting of Collaboration with TMSUK
Samurai Humanoid KIYOMORI: 2nd Brother of WABAIN-2 Visited Munakata Shrine
Prayed for the Safety of All the Robots in the World
3-Moment Compensatory Bipedal Walking Control Extending the ZMP Criteria

\[
\sum_{i} m_i (r_i - r_{ZMP}) \times (\dot{r}_i - G)
\]

\[
- \sum_{k} \{(r_{Fk} - r_{ZMP}) \times F_k + M_k\} = 0
\]
How to walk with balance

Stability criterion for biped robot based on ZMP (Zero Moment Point)

- ZMP: a point where the total forces and moments acting on the robot are zero
- ZMP trajectory: set arbitrarily within the support polygon

![Diagram showing ZMP trajectory, foot trajectory, and stable region with labels for force and moment](image)

Compensatory motion to keep the balance, computed using ZMP equation

March 18, 2005
ZMP Equation and the Coordinate Systems

\[ \sum_{i} m_i (r_i - r_P) \times (\ddot{r}_i - G) \]

All Particles

\[ \sum_{k} \{(r_{Fk} - r_P) \times F_k + M_k\} + T = 0 \]

All Points

ZMP Equation

\[ \sum_{i} m_i (r_i - r_{ZMP}) \times (\ddot{r}_i - G) \]

All Particles

\[ \sum_{k} \{(r_{Fk} - r_{ZMP}) \times F_k + M_k\} = 0 \]

All Points

\[ \sum_{i} m_i (\ddot{r}_i - \ddot{r}_{ZMP}) \times \{ \ddot{r}_i + \dddot{Q} - \ddot{G} \}
+ \dddot{\omega} \times \dddot{r}_i + 2 \dddot{\omega} \times \dot{\dddot{r}}_i + \ddot{\omega} \times (\dddot{\omega} \times \dddot{r}_i) \} \]

All Points

\[ \sum_{k} \{(r_{Fk} - r_{ZMP}) \times F_k + M_k\} = 0 \]

\[ \sum_{k} \{(r_{Fk} - r_{ZMP}) \times F_k + M_k\} = 0 \]

All Points

\[ m_i \]: mass of particle \( i \)
\[ r_i \]: position vector of particle \( i \)
\[ r_P \]: position vector of \( P \)
\[ T \]: total torque acting on \( P \)
\[ G \]: gravity acceleration vector
\[ O-XYZ \]: absolute coordinate system
\[ O-XYZ \]: moving coordinate system

March 18, 2005
Iterative Computation Algorithm to Converge ZMP/Moment Error

Initial parameters;
Foot trajectory,
Initial trunk and waist trajectories,
ZMP trajectory, and
\( \varepsilon_M \) (a tolerance level moment error)

1. Compute walking pattern using initial waist motion
2. Compute moments \( M \) generated by lower-limbs
3. Compute compensatory trunk and waist motion
   \( \bar{x}_T, \bar{y}_T, \bar{x}_W, \bar{y}_W \)
   using linear model (FFT&IFFT)
4. Compute walking pattern using compensatory waist motion
5. Compute moment errors (\( eM \)) between calculated ZMP and planned ZMP

\[ M = M_{LL} + E_n \]
\[ E_n = E_{n-1} + \text{Gain} \cdot eM_{(n-1)} \]

Moment errors (\( eM \))

Iterative computation to derive motion pattern

Repeat

\( eM < \varepsilon_M \)?

Yes

Complete walking pattern

No

March 18, 2005
WABIAN-2R Goes to Streets, but Many Problems!

We need more efforts for higher usability in the real world

Special Economical Zone for Robot Test and Experiment in Fukuoka
Biped Robot That Can Carry a Human: WL-16

Open Experiment at Okubo Campus of Waseda in 2006
WL-16 Goes to the US
Carrying 170 People in NextFest 2007
Towards Vocal Humanoid Robot: WT Series (2000-)
WT-5’s Mechanism

Sound Source
Vocal Cords
Out Put
Lips
Soft Palate
Tongue
Nasal Cavity
Palate
Tongue
Sound Source
Vocal Cords
Airflow from Lungs

WT-5’s Mechanism
Human Vocal Cords

Structure of Vocal Cords

Vocal Fold Vibration

Phase Difference in Glottal Closure Between Upper Part and Lower Part

※戸幾一郎: 発声機構の面よりみた喉頭の病態生理、耳鼻臨床 (1966)
WT-5’s Vocal Cords

Developed New Vocal Cords Mimicking Human Biomechanical Structure

- Using the Thermoplastic Rubber “Septon”
- Same Size as Human (Adult Male)

* Thermoplastic Rubber by Kuraray Co
Voiced/Unvoiced Sounds Switching Mechanism

- Glottal Opening/Closing Control Mechanism by using Arms Mimicking Human Arytenoid Cartilages
Modeling of Elastic Tongue

Elastic Tongue Shape

Rubber (EPDM)

Applicable to All Elastic Body

Control Point

Simulate

Modeling of Tongue as Connection of Rigid Links

Rigid Links

Applicable to All Elastic Body
Modeling of Elastic Tongue

Virtual Displacement \((\delta_x, \delta_y)\) by Force \(F\),
\[
\begin{align*}
\delta_x &= x_n - P_x \\
\delta_y &= y_n - P_y
\end{align*}
\]  \( (3) \)

Potential Energy (by Virtual Work Principle)
\[
U = \frac{1}{2} k_1 \left( \frac{\pi}{2} - q_1 \right)^2 + \sum_{i=2}^{n+1} \frac{1}{2} k_i q_i^2 + F_x \delta_x + F_y \delta_y
\]  \( (4) \)

Reflected by Hooke’s Law

Kinetic Energy \(T = 0\) (Stationary)
Lagrange’s Equations of Motion \(L = T - U\)
\[
\frac{d}{dt} \left( \frac{\partial L}{\partial \dot{q}_i} \right) - \frac{\partial L}{\partial q_i} = -\frac{\partial U}{\partial q_i} = 0 \quad (i = 1, 2, \ldots, n)
\]  \( (5) \)

Newton-Raphson Method

Link Angles \((q_1, q_2, \ldots, q_n)\)
Towards Vocal Humanoid Robot: WT Series

Robot Vocal Organs

Human Vocal Organs

Kotaro Fukui Team

Jump!
Flutist Robot for Simulating Human Flute Playing: WF-4 (1990- )

Mr. Wakamatsu: Technical Advisor

Gifu-Waseda WABOT-HOUSE Project
Waseda Flutist No. 4 Refined IV
Lips Mechanism Design

Lips: 3-DOFs
Waseda Flutist No.4 Refined IV
Lips Mechanism Motion
Waseda Flutist No.4 Refined IV
Tonguing Mechanism Design

Tongue: 1-DOF
Waseda Flutist No.4 Refined IV
Tong Mechanism Motion (Tonging)
Vibrato Mechanism

Human Vocal Cords

Intermediate

Professional

Mukai (1987)

Human-like Vibrato Mechanism

Vibrato Mechanism

High Amplitude

Low Amplitude

4 [Hz], A4
Lung Mechanism

- Shaft
- Link
- AC Servomotor

Dimensions:
- 398 [mm]
- 413 [mm]
Finger Mechanisms

Link mechanism

DC Motor

pulley

Outer Tube
Teflon-lined Wire
(Chukoh Chemical Industries LTD)

Supported by SokidWorks K.K

The Robotics Society of Japan
What is good flute sound?: Evaluation Index

**Items**

- **V**: Total Sound Volume
- **H**: Average of Harmonics
- **Hs**: Average of Semi-Harmonics
- **Hd**: Even Har. – Odd Har.
- **W1, W2**: Weightings

**F**<sub>(Note Pitch)</sub> = **V** + **w**<sub>1</sub><sub>R</sub> × (**H** - **Hs**) + **w**<sub>2</sub><sub>R</sub> × **Hd**

R [Pitch Range] = {Low, Middle, High}
WF-4’s Flute Play:
The Flight of the Bumble-Bee
(Rimsky-Korsakov)
Duet between Human and WF-4
Saxophonist Robot: WAS-2

Total: 22 DOFs

<table>
<thead>
<tr>
<th>Part</th>
<th>Degrees of Freedom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump</td>
<td>1 DOF</td>
</tr>
<tr>
<td>Valve</td>
<td>1 DOF</td>
</tr>
<tr>
<td>Lip</td>
<td>3-DOF</td>
</tr>
<tr>
<td>Tongue</td>
<td>1-DOF</td>
</tr>
<tr>
<td>Fingers</td>
<td>16-DOFs</td>
</tr>
</tbody>
</table>

New Mouth & Hand Mechanism
New Mouth Mechanism

Overview

<table>
<thead>
<tr>
<th>Part</th>
<th>No. of Degree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper lip</td>
<td>1</td>
</tr>
<tr>
<td>Sideway</td>
<td>(1)</td>
</tr>
<tr>
<td>Lower lip</td>
<td>1</td>
</tr>
</tbody>
</table>

WAS-2
Development of a Human-Like Hand

Video

MP関節: Roll
Demo Play of WAS-2: Sing Sing Sing
Emotion Expression Humanoid **EYE-Chan**: WE-4RII for Modeling Human Mind

<table>
<thead>
<tr>
<th>Part</th>
<th>DOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neck</td>
<td>4</td>
</tr>
<tr>
<td>Eyes</td>
<td>3</td>
</tr>
<tr>
<td>Eyelids</td>
<td>6</td>
</tr>
<tr>
<td>Eyebrows</td>
<td>8</td>
</tr>
<tr>
<td>Lips</td>
<td>4</td>
</tr>
<tr>
<td>Jaw</td>
<td>1</td>
</tr>
<tr>
<td>Lung</td>
<td>1</td>
</tr>
<tr>
<td>Waist</td>
<td>2</td>
</tr>
<tr>
<td>Arms</td>
<td>18</td>
</tr>
<tr>
<td>Hand</td>
<td>12</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>59</strong></td>
</tr>
</tbody>
</table>
WE-4 (Waseda Eye No.4)

Expressions
- Eyebrows
- Eyelids
- Facial Color
- Lips
- Voice
- Neck
- Waist
- Lung (Breath)

Sensors
- Visual (CCD Camera)
- Auditory (Microphone)
- Olfactory (Gas Sensor)
- Tactile (FSR)
- Temperature (Thermistor)
Control System and Personality

Environment

Motion - Reflex - Sensing

Behavior - Intelligence - Recognition

Expression Personality - Emotion - Sensing Personality

Total Personality
Equations of Emotion

\[ M_{t+\Delta t} = M_t + \Delta M \]

- \( M_t = (a_t, p_t, c_t) \)
- \( \Delta M = (\Delta a, \Delta p, \Delta c) \)
- \( a_t : \) Activation
- \( p_t : \) Pleasantness
- \( c_t : \) Certainty
Emotion Mapping in Mental Space

E = \{\text{Happiness, Anger, Surprise, Sadness, Fear, Disgust, Neutral}\}

emotion \in E

From Eq. of Motion to Eq. Emotion

Equation of Motion (運動方程式)
\[ m \ddot{x} + \gamma \dot{x} + k x = F(t) \]

Equations of Emotion (情動方程式)
\[ M \dddot{E} + \Gamma \ddot{E} + KE = F_{EA} \]

\( E \): Emotion Vector, \( F_{EA} \): Emotional Appraisal

Emotional Coefficient Matrix (情動係数行列)
\( M \): Emotional Inertia Matrix (情動慣性)
\( \Gamma \): Emotional Viscosity Matrix (情動粘性)
\( K \): Emotional Stiffness Matrix (情動弾性)
Emotional Dynamics

Emotional Attenuation Coefficient (情動減衰係數)

$$\zeta_i = \frac{\gamma_i^*}{2\sqrt{m_i^* k_i^*}}$$

Emotional Natural Angular Frequency (情動固有周波数)

$$\det \begin{vmatrix} K - \omega_{ni}^2 M \end{vmatrix} = 0$$

$$\omega_{ni} = \sqrt{\frac{k_i^*}{m_i^*}}$$

$$m_i^* = \phi_i^T M \phi_i \quad \gamma_i^* = \phi_i^T \Gamma \phi_i$$

$$k_i^* = \phi_i^T K \phi_i \quad \phi_i : Eigenvector$$
## Sensing Personality Table

<table>
<thead>
<tr>
<th>Stimulus</th>
<th>Sensation</th>
<th>Δa</th>
<th>Δp</th>
<th>Δc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual</td>
<td>Loose Sight of the Target</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Discover the Target</td>
<td>+</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>Dazzling Light</td>
<td>+</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Target is Near</td>
<td>+</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Tactile</td>
<td>Pushed</td>
<td>+</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Pushed Strongly</td>
<td>+</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Stroked</td>
<td>+</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Hit</td>
<td>+</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Auditory</td>
<td>Loud Sound</td>
<td>+</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Temperature</td>
<td>Heat</td>
<td>0</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Olfactory</td>
<td>Alcohol</td>
<td>-</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Ammonia</td>
<td>+</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Cigarette Smoke</td>
<td>+</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>No Sense</td>
<td>-</td>
<td>→0*</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>No Stimulus</td>
<td>-</td>
<td>→0*</td>
<td>0</td>
</tr>
</tbody>
</table>

* “→0” means to converge at “0”
Expression Personality

\[
\begin{bmatrix}
E_o
\end{bmatrix} = \begin{bmatrix}
\text{Expression Personality Matrix}
\end{bmatrix} \begin{bmatrix}
E_i
\end{bmatrix}
\]

\(E_i\): Input Emotion, \(E_o\): Output Emotion
Demos of EYE-Chan

Neutral

Wakes up
Additional Demos

Doing exercise using a dumbbell

More Behaviors

Addition of Consciousness
WABIAN-2 + EYE-Chan = KOBIAN
Emotional Expressions of KOBIAN
The End

Thank you!