Remotely Augmented Reality Intelligent Cognitive Robotics for Personally Assisted Living under Unstructured Environment

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Objectives:

• To develop remote augmented reality intelligent cognitive robotics for personally assisted living under unstructured environment.

• The main research issues are how to let the robot deal with the complex and dynamic environment and have the personal assistant ability either in remote distance or actual in-situ presence.
It is proposed to focus on innovative research in two relevant areas of application needs especially in remote augmented reality intelligent cognitive robotics for personally assisted living under unstructured environment. The research issues include:

- **A. Medical and Healthcare Robotics**
  - (1). Issues in Intuitive physical human-robot Interaction between caregivers, patients, robots and sensing, perception, and action.
  - (2). Issues in Multisensor fusion and integration to enable automated understanding of human behavior and real-time user interaction and assistances.
  - (3). Issues in Emotion understanding, modeling, and classification for activity recognition, physiologic data processing, and multi-modal perception.
B. Intelligent Service Robotics

• (1). Issues in Dexterous hands and safe manipulators with skill learning, modeling and transfer.

• (2). Issues in real-world 3D perception, mapping and navigation to accommodate unstructured and dynamic environment.

• (3). Issues in cognition systems for smooth interaction with users and deployment in domains where there is limited opportunities for user training and ensuring system robustness.

• (4). Issues in skill acquisition to solve novel tasks with continuously improving performance through advances in perception, representation, machine learning, cognition, planning, and control research.

• (5). Issues in safe robots through advances in perception and control to detect objects and persons and predict possible safety hazards as well as avoid contact damage.
• Remote Augmented Reality Bi-directional Adaptive Force Reflection and Impedance Control Dual Arm Robot for Intelligent Service Robotics
Structure

Motor (1 DOF)
- Impedance control (one DOF)
- Compliance control (one DOF)

Multi-DOF manipulator
- Impedance control
- Compliance control
- Gravity compensation
- Auxiliary force control

Application
- Force balance
- Learning & play
- Massage
- Endoscope
1-DOF Adaptive Impedance control
The PMAC card provides 1ms servo interrupt time for the routine of the control, and sends out the control command to the servo driver through the D/A converter.
From Kirchhoff’s voltage law, we obtain

$$LI_a + RI_a = V - V_b \quad (1)$$

Where $I_a$ is the armature current, $V$ is the applied armature voltage, $V_b$ is the back electromotive force (back emf). R and L denotes resistance and inductance respectively. Since the current-carrying armature is rotating in a magnetic field, its voltage is proportional to speed. Thus,

$$V_b = K_b \dot{\theta} \quad (2)$$

Where $V_b$ is the back emf, $K_b$ is back emf constant, and $\dot{\theta}$ is the angular velocity of the motor.

The torque developed by the motor is proportional to the armature current, thus,

$$\tau = K_t I_a \quad (3)$$

Where $K_t$ is the torque developed by the motor and $I_a$ is the motor torque constant.
To find the transfer function of the motor, we first substitute Eq. (2) into (1) and take the Laplace transform, yielding

\[ I_d(s) = \frac{V - K_b s \Theta(s)}{Ls + R} \]  

(4)

From Newton second law and Laplace transform, we obtain

\[ J s^2 \dot{\theta} + C s \dot{\theta} = \tau - \tau_d \]  

(5)

Substituted Eq. (3) and (4) into Eq. (5) yields

\[ \left(J s^2 + C s + \frac{K_t K_b s}{Ls + R}\right) \Theta(s) = \frac{K_t V}{Ls + R} - \tau_d \]  

(6)

Assume \( L << R \) thus

\[ \Theta(s) \left[ J s^2 + (C + K_t K_b / R) s \right] = \frac{K_t}{R} V(s) - \tau_d \]  

(7)
\[ \left[ \Theta_{\text{com}}(s) - \Theta_{\text{feedback}}(s) \right] \left( K_{\text{impedance}} + K_I/s \right) - sK_D \Theta_{\text{com}}(s) - \text{Torque}_{\text{load}} = \text{Torque}_{\text{command}} \quad (8) \]

Denote torque command.

\[ \text{Torque}_{\text{com}} = \left[ \Theta_{\text{com}}(s) - \Theta_{\text{feedback}}(s) \right] \left( K_{\text{impedance}} + K_I/s \right) - s \Theta_{\text{com}}(s) K_D - \left\{ \omega_{\text{feedback}}(s) \left[ Js + (C + K_I K_b / R) \right] + \tau_d \right\} \quad (9) \]
Adaptive Impedance Control Block Diagram
Adaptive Impedance Control Block Parameters

\[ \Theta_{\text{com}}(s) : \text{Command position} \]

\[ \Theta_{\text{feedback}}(s) : \text{Actual feedback position} \]

R : Resistor of the servo motor driver

J : Inertial of the system load

C : Viscosity coefficient of the system load

\[ K_t : \text{Torque constant} \]

\[ K_b : \text{Back EMF coefficient} \]

\[ K_{\text{impedance}} : \text{Impedance gain} \]

\[ \tau_d : \text{Disturbance torque} \]
According to the diagram, close loop transfer function between B and C is

\[
T_{C/B}(s) = \frac{\frac{K_t}{Js + b}}{1 + \frac{1}{Js + b} \left[ Js + (C + K_t K_b / R) \right]} \tag{10}
\]

\[
\text{Output}_D(s) = \text{Input}_B(s)\left\{ \frac{\frac{K_t}{Js + b}}{1 + \frac{1}{Js + b} \left[ Js + (C + K_t K_b / R) \right]} \left[ 1 + \frac{1}{Js + b} \left[ Js + (C + K_t K_b / R) \right] \right] \right\} \frac{1}{s} \tag{11}
\]

and the relationship between B and D is

\[
\text{following error}_A(s) = \text{Desired position} - \text{Output}_D = \Theta_{\text{com}}(s) - \text{Input}_B(s)\left\{ \frac{\frac{K_t}{Js + b}}{1 + \frac{1}{Js + b} \left[ Js + (C + K_t K_b / R) \right]} \left[ 1 + \frac{1}{Js + b} \left[ Js + (C + K_t K_b / R) \right] \right] \right\} \frac{1}{s} \tag{12}
\]
From the outer position loop to observe the inner current control loop of the system, the bandwidth of the inner current control loop of the system is wide enough. Therefore, we assume

\[
T_{C/B}(s) \approx A_{\text{tor vel}} \quad (13)
\]

where \(A_{\text{tor vel}}\) defined as the gain between impedance torque input(B) and velocity output(C).

Substituting Eq.(13) into Eq.(12) yields,

\[
\text{following error}_{A}(s) = \Theta_{\text{com}}(s) - \frac{\text{Input}_{B}(s) \cdot A_{\text{tor vel}}}{s} \quad (14)
\]
Output velocity at C can be expressed as

$$Output_C(s) = Input_B(s)T_{C/B} = following\_error_A(s)T_{B/A}(s)T_{C/B} \quad (15)$$

Substituting Eq.(13) and (14) to Eq.(15), we obtain

$$Output_C(s) \approx \left\{ \frac{\Theta_{com}(s)s - Input_B(s)A_{tor\_vel}}{s} \right\}T_{B/A}(s)A_{tor\_vel} \quad (16)$$

To obtain the constant speed, we design the impedance gain as

$$T_{B/A}(s) = Impedance_{gain}(s) = \frac{Q\Theta_{com}(s)}{\Theta_{com}(s)s - Input_B(s)A_{tor\_vel}} \frac{1}{A_{tor\_vel}} \quad (17)$$

Substituting Eq.(17) to Eq.(16) and multiplying s yield,

$$Output_C(s) \approx Q\Theta_{com}(s) \quad (18)$$
Simulation Results: Adaptive Impedance Control

Fig A. Without constant speed portion because it uses the fixed constant value of impedance gain

Fig B. Constant speed at 1000rpm because it uses the adaptive impedance gain

Fig C. Increase the constant speed to 2000rpm with adaptive impedance gain

Fig D. Decrease the constant speed range with adaptive impedance gain
Command VS. Actual position response

- **Command (Target position at 1000mm)**
- **Start slow down away target 100mm (900mm constant speed range)**
- **Start slow down away target 500mm (500mm constant speed range)**
- **Full slow down range (without constant speed range)**
As shown in this figure, the constant impedance gain results in quick decay of speed. However, there are many applications need constant speed, such as welding robots perform the weld and service robots deliver objects to human.
We can set the range gain \( (K_R) \) to determine the constant speed range.
We can set constant speed gain \( K_{C.S} \) to determine the constant speed magnitude.
Adaptive Impedance Control with Observer (K_{cs}=5,K_{de}=13)

Adaptive Impedance Control without Observer (K_{cs}=5,K_{de}=13)

The ripple torque causes the speed output with ripple

Zoom in right side speed result of above figure

Adaptive Impedance Control with Observer (Zoom In) (K_{cs}=5,K_{de}=13)

Adaptive Impedance Control without Observer (Zoom In) (K_{cs}=5,K_{de}=13)

Smooth Speed
Adaptive Impedance Control Block Diagram
Without Integral Controller

(i)

Without Integral Controller (Zoom In)

(ii)

With Integral Controller

(iii)
Multi-DOF Manipulator
System Architecture

DC motors

1. 2. n.

PC-Based Controller

Motion Control Kernel

PC

DA Convertor

Encoder

Voltage Command

Motor Driver

DA Convertor

DA Convertor

DA Convertor
Denavit-Hartenberg' (DH) form
### Denavit-Hartenberg' (DH) form

<table>
<thead>
<tr>
<th>$i$</th>
<th>$\theta_i$</th>
<th>$d_i$</th>
<th>$\alpha_i$</th>
<th>$a_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\theta_i + 0^0$</td>
<td>$d_1 = 7.5\text{cm}$</td>
<td>$90^0$</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>$\theta_2 - 90^0$</td>
<td>0</td>
<td>$90^0$</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>$\theta_3 - 90^0$</td>
<td>$d_3 = -30\text{cm}$</td>
<td>$90^0$</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>$\theta_4 + 0^0$</td>
<td>0</td>
<td>$0^0$</td>
<td>$a_4 = 30\text{cm}$</td>
</tr>
</tbody>
</table>

$$T_{i-1}^i = \begin{bmatrix}
\cos \theta_i & -\sin \theta_i \cos \alpha_i & \sin \theta_i \sin \alpha_i & a_i \cos \theta_i \\
\sin \theta_i & \cos \theta_i \cos \alpha_i & -\cos \theta_i \sin \alpha_i & a_i \sin \theta_i \\
0 & \sin \alpha_i & \cos \alpha_i & d_i \\
0 & 0 & 0 & 1
\end{bmatrix}$$

$$T_4^0 = T_1^0 \cdot T_2^1 \cdot T_3^2 \cdot T_4^3 = \begin{bmatrix}R_{4 \times 3}^0 & P_{4 \times 1}^0 \\ 0 & 1 \end{bmatrix}$$
Experimental Results of Adaptive Impedance Control with 4-D.O.F Robot Arm
Multi-DOF Impedance Control Structure

Adaptive Impedance Generator $K(p)$

- $P_d$: Desired position
- $\frac{dp}{dt}$: Velocity feedback
- Integral activated
- Dead band
- $J(q)$: Jacobian matrix
- $J^T(q)$: Transpose of Jacobian
- $J(q)$: Updated command torque
- $G(q)$: Gain function
- $1/s$: Integrator
- $\frac{1}{s}$: Derivative
- $\dot{q}$: Velocity
- $q$: Position
- $F_{rea}$: External force

Block Diagram:

1. Desired position $P_d$ to Impedance gain
2. Velocity feedback $\frac{dp}{dt}$ to Impedance gain
3. Integral activated
4. Dead band
5. $J(q)$ to $1/s$
6. $J^T(q)$ to $1/s$
7. $C(q, \dot{q})$ to $1/s$
8. Robot Arm
9. $G(q)$
10. $E$ to $1/s$
11. $F_{rea}$

Control Logic:

- Position following error
- Dynamic Impedance Output
- Impedance calculated torque
- Integral gain calculated torque
- Constant speed range
- Slow down range
- Slow down rate

Feedback Loop:

- Position feedback
- Speed feedback

System Equations:

$$\dot{q} = J(q)^{-1}(I(q) + G(q))$$

Controller Design:

1. Adaptive Impedance Generator $K(p)$
2. Impedance Control Structure
3. Multi-DOF Impedance Control System
Gravity Compensator
Gravity Compensator
General Control Block Diagram

Desired Position $q_{com}(s)$

Desired Controller $C(s)$

+ + +

Command Torque

+ -

Motor Torque Constant $K_m$

Amplifier

Torque Control Loop (Servo Driver)

Differential 1:50

Robot Arm

$G(q)$

$C(q, \dot{q})$

$q(s)$

$\dot{q}(s)$

1/s

Current Feedback

Updated Command Torque
L_1: Link_1
r_1: distance of CoM1

L_2: Link_2
r_2: distance of CoM2

L_3: Link_3
r_3: distance of CoM3
Vector Projection in 3 Dimension

\[ \vec{M} = \vec{r} \times \vec{F} \]
\[ \tau = \vec{M} \cdot \vec{e} = [\vec{r} \times \vec{F}] \cdot \vec{e} \]
\[ \vec{\tau} = \{[\vec{r} \times \vec{F}] \cdot \vec{e}\} \vec{e} \]

\(\vec{F}\): force vector in 3D space
\(\vec{r}\): position vector in 3D space
\(\vec{e}\): unit vector in 3D space
Vector Projection in Multi-DOF

\[ \vec{F}_i = \sum m_i g \vec{i} \]

\[ R_{\theta_i} = \begin{bmatrix} \cos \theta_i & -\sin \theta_i & 0 \\ \sin \theta_i & \cos \theta_i & 0 \\ 0 & 0 & 1 \end{bmatrix} \]

\[ R_{\alpha_i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \alpha_i & -\sin \alpha_i \\ 0 & \sin \alpha_i & \cos \alpha_i \end{bmatrix} \]

\[ T_{r_i}^{0\times4} = T_1^0 \cdot T_2^1 \cdots T_{r_i}^{i-1}, \quad \vec{r}_i = \begin{bmatrix} T_{r_i}^0 (1,4) \\ T_{r_i}^0 (2,4) \\ T_{r_i}^0 (3,4) \end{bmatrix} \]

\[ T_i \sum m_i g \vec{i} = \sum e_i^0 = R_{\theta_1} \cdot R_{\alpha_1} \cdot R_{\theta_2} \cdot R_{\alpha_2} \cdots R_{\theta_{i-1}} \cdot R_{\alpha_{i-1}} \cdot \vec{R}, \quad R = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \]
\[ \tau_1 = [\vec{r}_1 \times \vec{F}_1] \cdot \vec{e}_1^0 = M_2 g^*(r_2) \cos(\theta_2) \sin(\theta_1) + M_3 g^*(L_2) \cos(\theta_2) \sin(\theta_1) + M_3 g^*(r_3) \cos(\theta_2) \sin(\theta_4) \sin(\theta_1) + \cos(\theta_1) \cos(\theta_3) \cos(\theta_4) + \sin(\theta_1) \sin(\theta_2) \sin(\theta_3) \cos(\theta_4) \]

\[ \tau_2 = [\vec{r}_2 \times \vec{F}_2] \cdot \vec{e}_2^0 = \cos(\theta_1) \left( M_2 g^*(r_2) \sin(\theta_2) + M_3 g^*(L_2) \sin(\theta_2) + M_3 g^*(r_3) \sin(\theta_4) \sin(\theta_2) - M_3 g^*(r_3) \cos(\theta_2) \sin(\theta_3) \cos(\theta_4) \right) \]

\[ \tau_3 = [\vec{r}_3 \times \vec{F}_3] \cdot \vec{e}_3^0 = M_3 g^*(r_3) \left( \cos(\theta_4) \sin(\theta_1) \sin(\theta_3) + \cos(\theta_1) \cos(\theta_3) \sin(\theta_2) \right) \]

\[ \tau_4 = [\vec{r}_4 \times \vec{F}_4] \cdot \vec{e}_4^0 = M_3 g^*(r_3) \left( \cos(\theta_1) \cos(\theta_2) \cos(\theta_4) + \cos(\theta_3) \sin(\theta_4) \sin(\theta_1) - \cos(\theta_1) \sin(\theta_4) \sin(\theta_2) \sin(\theta_3) \right) \]
Result and Demo (Gravity)
New Arm_Gravity compensator & auxiliary force.avi
Auxiliary Force/Torque Control
Gravity compensation:

\[ G_i = \sum_{i=1}^{n} \{ (\vec{r} \times \vec{F}' \} \cdot \vec{e} \} \]

\[ \vec{e} = T_i^{Base \ [Rot]} \ast T_i^{[Joint\_Dir]} \]

Angular momentum and angular impulse principle:

\[ M_{auxiliary} \Delta t = I \Delta \omega \]

\[ M_{auxiliary} = I \frac{\Delta \omega}{\Delta t} \]

\[ I = \frac{1}{12} mr^2 \]
Parabolic Curve

\[ \Delta t = a \cdot \Delta \omega^2 + k \]

\[ M_{\text{auxiliary}} = I \frac{\Delta \omega}{a \cdot \Delta \omega^2 + k} \]
Result and Demo

**Gravity compensation**

**Parabola function**

**Angular momentum and angular impulse principle**

**Dexterous Gravity Compensator**
gravity_compensator_compare(small_x2).avi
ArmflipA-P1070460.MOV
New Arm_teach&play.avi
Force Counterbalance Control
Motivation

[Diagram showing a red circle with an 'X' over a photo of a construction site, and a thought bubble with a light bulb and action figures of Iron Man.]
Impedance Control Diagram

Simple impedance control law:

\[ \tau = K(X_d - X) \]
Impedance Control Algorithm

\[ \begin{align*}
K_{A6\times6} & \quad J^T_{6\times6} \\
F_{6\times1} & \quad \tau_{6\times1} \\
G_{6\times1} & \quad (K_Ds)_{6\times6}
\end{align*} \]
Force/Weight Balance Control Algorithm

External Force

Dexterous Gravity Compensator (open loop)

Weight Estimate Algorithm (closed loop)

Robot Arm

Trigger
Weight Estimate Algorithm

\[ M_i = k \Delta \theta_i \] (closed loop)

\[ G_i = \Sigma \{(rxF) \cdot e\} = M_i \]

\[ F = \bar{F}, \quad \bar{r} \]

\[ m g_{\text{sum}} = m g_{\text{self}} + m g_{\text{external}} \]

\[ \tau_i / L_i \]
Without_force_balance.avi
with-force_balance.avi
Dynamic equation of robot manipulator

\[ I(q)q + C(q, q)q + G(q) = \tau_{act} + \tau_{rea} \]
Transformation of the joint angle and the Cartesian coordinate

\[ p = f(q) \]

\[ J(q) = \frac{\partial f(q)}{\partial q} \]

\[ \dot{p} = J(q) \dot{q} \quad \tau_{rea} = J(q)^T F_{rea} \]

\[ I(q) \ddot{q} + C(q, q) \dot{q} + G(q) = \tau_{act} + \tau_{rea} \]

\[ I(q) \ddot{q} + C(q, q) \dot{q} + G(q) = \tau_{act} + J(q)^T F_{rea} \]
\[ I(q) \dot{q} + C(q, q) \dot{q} + G(q) = \tau_{act} + J(q)^T F_{rea} \]

\[ M \ddot{p} + C \dot{p} + Kp = F_{rea} \]

\[ \tau_{act} = I(q)J(q)^{-1}\{M^{-1}[F_{rea} - C \dot{p} - Kp] - J(q) \dot{q}\} \]

\[ + C(q, q) \dot{q} + G(q) - J(q)^T F_{rea} \]
\[ M \dot{p} + C \dot{p} + Kp = F_{rea} \implies p = M^{-1}(F_{rea} - C \dot{p} - Kp) \]

Because \( p = J(q)q \) \( \implies p = J(q)q + J(q)\dot{q} \)

\[ \implies q = J(q)^{-1}(p - J(q)\dot{q}) \]

\[ \implies q = J(q)^{-1}(M^{-1}(F_{rea} - C \dot{p} - Kp) - J(q)q) \]

\[ I(q)q + C(q, q)\dot{q} + G(q) = \tau_{act} + J(q)^T F_{rea} \]

\[ \tau_{act} = I(q)J(q)^{-1}\{M^{-1}[F_{rea} - C \dot{p} - Kp] - J(q)q\} + C(q, q)\dot{q} + G(q) - J(q)^T F_{rea} \]
Adaptive Impedance Control

\[
\tau_{act} = I(q)J(q)^{-1}\{M^{-1}[F_{rea} - C p - Kp] - J(q)q\} + C(q,q)q + G(q) - J(q)^T F_{rea}
\]
Arm control

- 3min_version.avi

Arm teach and play simultaneous auto play
Gender Recognition
1. Face detection
2. Preprocess
3. Feature extraction
4. Classifier
5. Ensemble learning
Gender Recognition

Male [ ]
Female [ ]
Unknown [ ]
Object Tracking

- Hybrid Discriminative Tracking
  - \textit{HDT} (proposed) — yellow
- \textit{MILTRack} (Babenko et al., CVPR’09) — blue
- \textit{FragTrack} (Grabner et al., ECCV’08) — green
- \textit{PROST} (Santner et al., CVPR’10) — red
Surveillance
3D visual tracking
Einstein Facial Exp. Demo
Einstein Interaction
• Facial+expression-min
  tsai\scenario_surprise.wmv

facial+expression-min
  tsai\scenario_disgust.wmv

facial+expression-min
  tsai\scenario_fearful.wmv
Remote Control - **SRSocket**

- **CListenSocket**
- **CClientSocket[*]**
- **Connect num**
- **Trans Cmd Queue**
- **Recv Cmd Queue**
- **Encode**
- **Decode**

**Kernel**

**SR-Socket** diagram:

- Listen
- Connect
- Inc
- Put
- Get
Remote Control - Command Format

- Command ID
- Parameter Number
- Para 1 Type
- Para 1
- Para 2 Type
- Para 2

Parameter Type

1. Int
2. CString
3. Word
4. Double
5. Long
6. Byte Stream
7. Byte Stream Packet
Remote Control: Android & iPhone

Android

iPhone
Thank You!


RST, Robotics Society of Taiwan