Developing Actuators with Rich Motor Properties for Emerging Humanoids

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Workshop on New Bodies for Cognitive Humanoids,
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Research efforts towards passive compliant systems

VIACTORS
The goal is to design, realize and evaluate new range of actuator groups exhibiting variable stiffness, variable damping or full impedance regulation principles.

AMARSi
The goal of AMARSi is a qualitative jump toward rich motor behaviour where novel mechanics, control and learning solutions are integrated with each other.
Aims to design, realize and test a new generation of humanoid and quadruped robotic platforms, powered by compliant actuators.

To study how compliance can be exploited through learning for more natural locomotion, safer interaction and reduced energy consumption.
COMAN passive compliant humanoid

- a full humanoid robot with a height of 110cm.
- 32 + (1) major degrees of freedom of freedom (arms/legs and torso and neck)
- intrinsic passive compliance in the actuation
- Joint torque sensing/active compliance
The CompAct™ Unit:
A fixed passive compliance actuator

- **Input pulley**: rigidly linked with the gear’s outer shaft
- **Output three spoke part**: linked with the external pulley through a spring arrangement
Fixed compliance actuator

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Diameter</td>
<td>70mm</td>
</tr>
<tr>
<td>Length</td>
<td>80mm</td>
</tr>
<tr>
<td>Power</td>
<td>190W</td>
</tr>
<tr>
<td>Gear Ratio</td>
<td>100:1</td>
</tr>
<tr>
<td>Peak torque</td>
<td>55Nm</td>
</tr>
<tr>
<td>Max rotary passive deflection</td>
<td>+/-0.18rad</td>
</tr>
<tr>
<td>Weight</td>
<td>0.52Kg</td>
</tr>
</tbody>
</table>

\[ K_S = 6 \cdot K_A \cdot (2 \cdot \cos \theta_s^2 - 1) \]
Leg mechanics

- Ankle pitch motor
- Series elastic module
- 6dof F/T sensor
- Passive foot toe
- Rigid linkage
- Ankle roll motor
- Sole loadcells
Compliant legs – First static steps

October 2010
Compliant legs-Dynamic walking

January 2011
COMAN tolerance to impacts
From legs to full body COmpliant HuMANoid (COMAN): Quick summary of updates

- Passive compliance added to
  - Hip joints
  - Torso joint (Pitch and yaw)
- Upper torso and arms
  - Passive compliance at shoulders and elbow
- On board controller
- Battery + BMS
**Hip joint**

- Serial mechanism
- Passive compliance at the hip flexion / extension

<table>
<thead>
<tr>
<th>Joint</th>
<th>New Hip</th>
<th>First Prototype</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Motion Range (°)</td>
<td>Torque (Nm)</td>
</tr>
<tr>
<td>Flex/Ext</td>
<td>+110, -45</td>
<td>55</td>
</tr>
<tr>
<td>Abd/Add</td>
<td>-60, +20</td>
<td>55</td>
</tr>
<tr>
<td>Rotation</td>
<td>+50, -50</td>
<td>55</td>
</tr>
</tbody>
</table>
Upper torso and neck

- Compliant Shoulder flexion
- PC104 controller
- Neck module
- Shoulder and neck motor controllers
- Battery pack and BMS system
Upper arm

- Fully decoupled
  - 3DOF Serial mechanism
- Passive compliance
  - Shoulder (flex/ext and abd/add) motions
  - Elbow flex/ext
Walking with efficiency

Conventional ZMP-Fixed and COM Height based walking

• How to reduce the energy consumption of humanoid walking?
  – Passive-dynamic walkers
  – Active Systems - Efficient trajectories
  – Use passive compliance to re-use energy

Energy consumption

Learn efficient trajectories
Passively-compliant robot COMAN learning to walk with varying CoM-height

Kormushev et. al., IROS 2011
Evolving policy parameterization

- **Fixed number of spline knots**
- **Dynamically changing number of knots**

Advantages:
- Faster convergence
- Efficient exploration
- Avoids local optima
- Decreased computation time
Real-world experiment

Cyclic trajectories

Average electric energy consumed per walking cycle

\[ E_j(t_1, t_2) = \int_{t_1}^{t_2} I_j(t) U_j(t) \, dt \]

\[ E(\tau) = \frac{1}{c} \sum_{j \in I} E_j(t_1, t_2) \]

\[ R(\tau) = e^{-kE(\tau)} \]

- Number of cycles: \( c = 4 \) (8 steps)
- Number of joints in sagittal plane: \(|J| = 6|\)

<table>
<thead>
<tr>
<th>No.</th>
<th>Phase description</th>
<th>Start time[s]</th>
<th>Duration[s]</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Wait 1</td>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>2</td>
<td>Knee bend</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>3</td>
<td>Wait 2</td>
<td>2.00</td>
<td>5.00</td>
</tr>
<tr>
<td>4</td>
<td>Transfer phase (Double)</td>
<td>7.00</td>
<td>0.60</td>
</tr>
<tr>
<td>5</td>
<td>Right single</td>
<td>7.60</td>
<td>0.50</td>
</tr>
<tr>
<td>6</td>
<td>Double</td>
<td>8.10</td>
<td>0.15</td>
</tr>
<tr>
<td>7</td>
<td>Left single</td>
<td>8.25</td>
<td>0.50</td>
</tr>
<tr>
<td>8</td>
<td>Double</td>
<td>8.75</td>
<td>0.15</td>
</tr>
<tr>
<td>9</td>
<td>Right single</td>
<td>8.90</td>
<td>0.50</td>
</tr>
<tr>
<td>10</td>
<td>Double</td>
<td>9.40</td>
<td>0.15</td>
</tr>
</tbody>
</table>
Real-world experiment

• 180 rollouts later…

Learned efficient trajectory

18% reduction of the energy consumption in the sagittal plane

Lowest energy achieved at rollout #126
Variable CoM-height walking

Fixed CoM-height

Variable CoM-height
COMAN tolerance to push and terrain disturbances
Experimental COM, COP, responses
Actuation: What is coming next?

Fixed stiffness joint

Variable stiffness joint

Variable damper

$K_T = 6 \cdot K_S$
Lever arm principle

Hybrid actuator:
Byeong-Sang Kim et al., ICRA 2010

Energy Efficient VSA:
L.C. Visser et al., ICRA 2010

AwAS: A. Jafari et al., IROS 2010

AwAS II
Jafari et al., ICRA 2011,
CompAct-VSA: Lever arm with variable pivot point principle

- **High Stiffness**
  - $L_1$, $L_2$
  - Force
  - Pivot
  - Spring

- **Low Stiffness**
  - $L_1$, $L_2$
  - Force
  - Pivot
  - Spring
CompAct-VSA: Realization

Variable Stiffness Module

- A) Link/Cam Connection
- B) Joint Axis
- C) Cam Shaped Lever Arm
- E) Cam Roller
- F) Rack/Pinion
- G) Stiffness Motor
- H) Springs
- P) Pivot Point

Variable stiffness module

Main joint actuator

Tsagarakis et al. IROS 2011
Stiffness & Passive deflection profiles

\[ K = \frac{2k_s \delta_1^2 \Delta^2}{(\Delta - \delta_1)^2}. \]
Elastic and pivot motor torques

Elastic torque

\[ \tau_E = \frac{2k_s \delta_1^2 \Delta^2 \theta_s}{(\Delta - \delta_1)^2} \]

Resistant torque of the pivot motor

\[ |\tau_R| = \frac{2k_s n^2 \theta_2 \theta_s^2 \Delta^3}{(\Delta - n \theta_2)^3}. \]
Stiffness response: Experimental results

- **Pivot Tracking**

- **Stiffness tracking**
VPDA - Variable physical damping actuator

**Motivation**
- Facilitates control
  - Damps vibration
  - Reduces control effort
  - Inherently passive
- Manage energy of the spring

**Principle & Features**
- Semi-Active Solution
- Introduces “real” physical damping
- Piezoelectric actuation
SEA + Variable physical damping actuator (VPDA)

**Principle**
Semi-Active Solution
Introduces “real” physical damping
Piezoelectric actuation

VPDA + SEA

Laffranchi et al. ICRA 2010  Tsagarakis et al. ICRA 2009
VPDA Prototype assembly
People involved

- **Locomotion/Balancing**: Zhibin Li, Luca Colasanto
- **Learning for locomotion**: Petar Kormushev, Barkan Ugurlu
- **Variable Impedance Actuators**: Matteo Laffranchi, Amir Jafari

Petar Kormushev  Zhibin Li  Matteo Laffranchi  Amir Jafari  Barkan Ugurlu  Luca Colasanto