Supplemental Materials for the Article “TACSEI: Tactile Sensing, State Estimation and Embodied Intelligence of a Soft Hand”

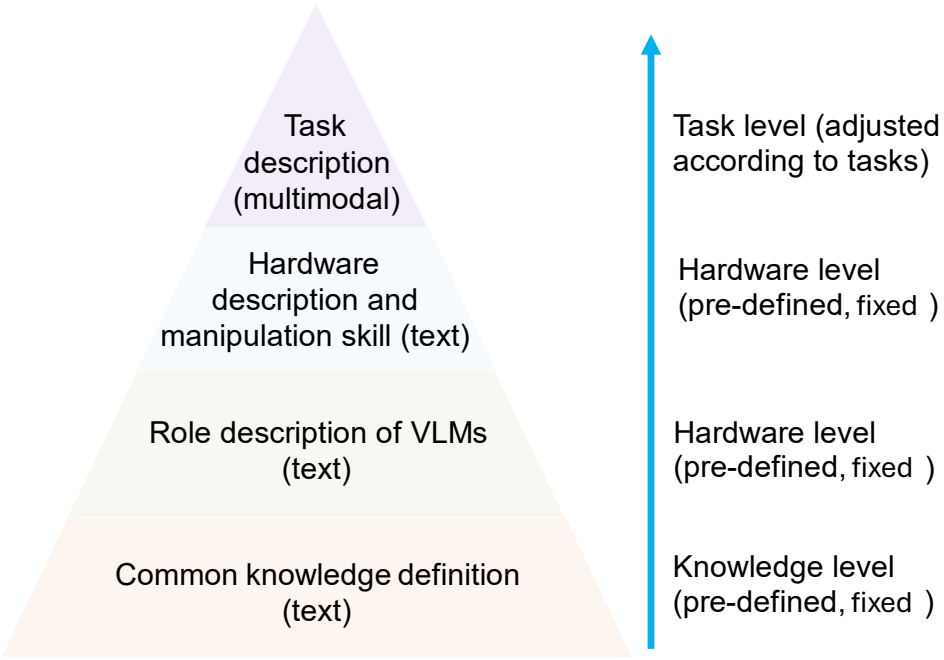

Fig. 1 Hierarchical pyramid prompt architecture of the VLMs for the proposed soft hand.

Prompt 1.1

Role: “system”
Content:
{
“type”: “text”, “text”:
For rotation task, the clockwise and counterclockwise are defined below:

1) All makers, labels and symbols on the object rotate towards the same direction with the object.
2) **Clockwise**: a marker on the object rotates from top to right, then bottom, then left.
3) **Counterclockwise**: a marker on the object rotates from top to left, then bottom, then right.

}

Prompt 1.2

Role: “system”
Content:
{
“type”: “text”, “text”:
For swing task, the clockwise and counterclockwise are defined below:

1) Focusing on a reference part on the ****upper body of object****,
2) **Clockwise**: The reference part moves from top to right of the view.
3) **Counterclockwise**: The reference part moves from top to left of the view.

}

Prompt 1.3

Role: “system”
Content:
{
“type”: “text”, “text”:
There are two cases for the bottle cap operation:

1) **Opening**: The bottle cap is **initially on the bottle**, and is **finally removed from the bottle**.
2) **Closing**: The bottle cap is **initially not on the bottle**, and **finally added to bottle**.

}

Prompt 2.1

Role: “system”
Content:
{
“type”: “text”, “text”:
You are the controller of a soft robotic gripper designed to manipulate objects. Based on the provided hardware description and control objectives, generate control signals and strategies for actuation and manipulation.
}

Prompt 2.2

Role: “system”
Content:
{
“type”: “text”, “text”:
You are a video analyzer.
}

Prompt 3.1

Role: “user”
Content:
{
“type”: “text”, “text”:

3.1.1 Gripper Design:

- The gripper is a humanoid right hand in a pre-grasp pose with three soft, silicone fingers:
  a) Thumb (TH): Positioned on the right side of the palm.
  b) First Finger (FF): Positioned on the left side of the palm.
  c) Middle Finger (MF): Positioned below the FF, on the same side.
- The TH and FF are opposite each other, while the MF aligns directionally with the FF.
- Each finger has multiple air chambers that can be independently actuated using compressed air.
- Action Mechanism: Inflating the chambers with compressed air causes the fingers to bend inward, enabling them to grasp objects.

3.1.2 Sensing ability:

- Each finger has a 4x8 tactile sensor array on its surface towards the target object to detect contact forces when interacting with an object.
- Sensors embedded between the air chambers measure forces generated during inflation, providing real-time feedback on finger states.

3.1.3 Control strategies:

- Pressure Range: Air pressure values range from 0 to 0.64 bar.
- Gripping Threshold: Fingers typically close and grip an object when the air pressure reaches approximately 0.4 bar.
- Smooth Transitions: Avoid sharp changes in air pressure for stability and precise control.
- Force Modulation:
  a) Adjusting real-time air pressure for each finger enables fine-grained control of the gripping force.
  b) Higher air pressure results in greater force applied toward the object.
- Finger Control: Independent control of the Thumb (TH), First Finger (FF), and Middle Finger (MF) allows for precise manipulation.
- Common Operations:
  a) Gripping (Grasping): Securely hold objects by inflating all active fingers to ~0.4 bar.
  b) Rotating: Adjust coordinated signals for the TH and FF while keeping the MF inactive (pressure = 0 bar).
  c) Swinging: Manipulate pressure across the fingers to tilt or swing the grasped object in a specific direction.
- Rotation Strategy:
  a) Use TH and FF to rotate a cylindrical object.
  b) Maintain a stable grip pressure, averaging 0.3 to 0.4 bar for both fingers.
  c) Keep the MF inactive (0 bar).
  d) Introduce a **0.5-cycle phase difference and an amplitude difference (0.15 ~ 0.25 bar) between the TH and FF signals**.
  e) **Larger average pressure and amplitude in the TH** signal rotates the object **toward the TH**.
  f) **Larger average pressure and amplitude in the FF** signal rotates the object **toward the FF**.
- Swinging Strategy:
  a) Adjust pressure among the fingers to swing the object:
  b) Toward **FF/MF**: Increase pressure on the **TH and MF**. Largely decrease pressure on the **FF**.
  c) Toward **TH**: Increase pressure on the **FF**. Largely decrease pressure on the **TH and MF**.

}

Prompt 4.1

Role: “user”
Content:
{
“type”: “text”, “text”:
Generate a signal sequence for each finger (Thumb - TH, First Finger - FF, and Middle Finger - MF) to gradually hold an object and then slowly release it.

4.1.1 Signal Arrays:
Save the air pressure values for each finger in separate arrays:
a) sig_th for the Thumb.
b) sig_ff for the First Finger.
c) sig_mf for the Middle Finger.
d) return only excutable Python code to generate the sequences, without useless strings.

4.1.2 Sequence Properties:
a) Each sequence must contain exactly 200 data points.
b) Air pressure values should remain within the range of 0 to 0.64 bar.

4.1.3 Expected Behavior:
a) Gradually increase air pressure to securely hold the object.
b) Maintain a stable grip at peak pressure (around 0.4 bar) for a short duration.
c) Slowly decrease pressure to release the object.
d) Smooth the control signal after generation.
}

Prompt 4.2

Role: “user”
Content:
{
“type”: “video”, “video”: *$the path of an attached video$*,

“type”: “text”, “text”:
Find the swing object held by the person and select a reference part on the **__upper body of the object__**, then describe the movement.
}

Prompt 4.3

Role: “user”
Content:
{
“type”: “text”, “text”:
Based on the demonstration result, generate signal sequences for each finger—Thumb (TH), First Finger (FF), and Middle Finger (MF)—to **__swing__** an object **__clockwise or counterclockwise__**.

4.4.1 Signal Arrays:
Save the air pressure values for each finger in separate arrays:

a) **__sig_th for the Thumb__**.
b) **__sig_ff for the First Finger__**.
c) **__sig_mf for the Middle Finger__**.
d) Return only executable Python code to generate the sequences, without useless strings.

4.4.2 Sequence Properties:

a) The length of signal sequence for each finger must be the 200.
b) Air pressure values should remain within the range of 0 to 0.64 bar.
c) Smooth the control signal after generation.

4.4.3 Considering the space relationship between the soft hand and object:

a) **__To swing clockwise: Swing toward the First Finger (FF)__** .
b) **__To swing counterclockwise: Swing toward the Thumb (TH)__** .
c) Using the **__Swinging Strategy__** in previous prompt in **__Prompt 3.1__** to achieve the swinging.

4.4.4 Expected Behavior:

a) Gradually increase air pressure for all fingers to grip the object.
b) Maintain the pose for a short duration.
c) Adjust air pressure to **__swing the object clockwise or counterclockwise as the demonstration result__**.
d) Maintain the pose until the end.

}

Prompt 4.4

Role: “user”
Content:
{
“type”: “video”, “video”: *$the path of an attached video$*,

“type”: “text”, “text”:
Find the rotating object and a reference symbol/letter/marker and describe them.
}

Prompt 4.5

Role: “user”
Content:
{
“type”: “text”, “text”: *$ insert the output from the Prompt 4.4 here$*,

“type”: “text”, “text”:
Focusing on the rotating object with the letter 'A' and considering the previous definition of the clockwise and counterclockwise. Tell me if the object is rotating **__clockwise__** or **__counterclockwise__**
}

Prompt 4.6

Role: “user”
Content:
{
“type”: “text”, “text”:
Based on the demonstration result, generate signal sequences for each finger—Thumb (TH), First Finger (FF), and Middle Finger (MF)—to **__rotate__** the object **__clockwise or counterclockwise__**.

4.7.1 Signal Arrays:
Save the air pressure values for each finger in separate arrays:

a) **__sig_th for the Thumb__**.
b) **__sig_ff for the First Finger__**.
c) **__sig_mf for the Middle Finger__**.
d) return only executable Python code to generate the sequences, without useless strings.

4.7.2 Sequence Properties:

a) The length of signal sequence for each finger must be the 500.
b) Air pressure values should remain within the range of **__0 to 0.64__** bar.
c) The signal sequences for related fingers must contain cyclic variations in air pressure.
d) Each cycle must consist of 20 data points for smooth air pressure modulation.

4.7.3 Considering the space relationship between the soft hand and object:

a) **__To rotate clockwise: Larger average pressure and amplitude in the FF__**.
b) **__To rotate counterclockwise: Larger average pressure and amplitude in the TH__**.
c) Using the **__Rotation Strategy__** in previous prompt in **__Prompt 3.1__** to achieve the rotation.

4.7.4 Expected Behavior:

a) Introduce cyclic variations in the air pressure of TH and FF to generate rotational torque, maintaining grip stability.
b) Ensure that the force/torque applied by TH and FF is coordinated to rotate the object **__clockwise or counterclockwise__** as the demonstration result.

}

Prompt 4.7

Role: “user”
Content:
{
“type”: “video”, “video”: *$the path of an attached video$*,

“type”: “text”, “text”:
Find the bottle and bottle cap and describe them.
}

Prompt 4.8

Role: “user”
Content:
{
“type”: “text”, “text”: *$ insert the output from the Prompt 4.7 here$*,

“type”: “text”, “text”:
Considering the previous definition and the status of bottle cap. Tell me if the person is **__opening or closing__** the bottle cap and explain the reason.
}

Prompt 4.9

Role: “user”
Content:
{
“type”: “text”, “text”:
Based on the demonstration result, generate signal sequences for each finger—Thumb (TH), First Finger (FF), and Middle Finger (MF)—to **__rotate__** a bottle cap for either **__opening or closing__**.

4.10.1 Signal Arrays:
Save the air pressure values for each finger in separate arrays:

a) **__sig_th for the Thumb__**.
b) **__sig_ff for the First Finger__**.
c) **__sig_mf for the Middle Finger__**.
d) return only executable Python code to generate the sequences, without useless strings.

4.10.2 Sequence Properties:

a) The length of signal sequence for each finger must be the 500.
b) Air pressure values should remain within the range of **__0 to 0.64__** bar.
c) The signal sequences for related fingers must contain cyclic variations in air pressure.
d) Each cycle must consist of 20 data points for smooth air pressure modulation.

4.10.3 Considering the space relationship between the soft hand and bottle cap:

a) **__Open: Rotate toward the Thumb (TH)__** .
b) **__Close: Rotate toward the First Finger (FF)__** .
c) Using the **__Rotation Strategy__** in previous prompt in **__Prompt 3.1__** to achieve the rotation.

4.10.4 Expected Behavior:

a) Introduce cyclic variations in the air pressure of TH and FF to generate rotational torque, maintaining grip stability.
b) Ensure that the force/torque applied by TH and FF is coordinated to rotate the object in the required direction **__opening or closing__** as the demonstration result.

}