**SUPPLEMENT MATERIALS**

**Title**

Actuating compact augmented reality devices by artificial muscle

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**Supplementary Figure 1. Design parameters and Pseudo-rigid-body models of CASA and BPS.** **a,** Top-view illustration and parameters of CASA. **b,** Top-view illustration and parameters of BPS. **c** and **d,** Pseudo-rigid-body model parameters of CASA (**c**) and BPS (**d**).



**Supplementary Figure 2**. **Temperature of the SMA wire during cyclic actuation of the CASA.** Temperature variation of the SMA wire measured using an infrared camera when the CASA is repeatedly actuated. The diameter of the SMA wire used in the experiment is 0.1 mm. The SMA wire is heated by Joule heating for 1 second and has a cooling time of 4 seconds in one actuation cycle.



**Supplementary Figure 3. Fabrication process of CASA. a,** preparation of the material for fabricating CASA including laser machined compliant beam, crimps and SMA wire. **b,** Before and after attaching crimp to SMA wire. **c,** Embedding SMA wire to compliant beam along the routing line. **d,** Multiple number of rows for increasing actuation force. **e,** Joining each compliant beam. **f,** Optical image of fabricated CASA.



**Supplementary Figure 4**. **Comparison of variable amplification structure.** Type of (**a**) Normal bias spring, (**b**) Dead weight bias, (**c**) Compliant beam bias type, (**d**) Right angle pull, and (**e**) Simple lever.



**Supplementary Figure 5. Experimental results of the CASA. a,** Actuation strain of CASAfor different applied voltages, where current was applied for 2 s. **b,** Actuation stroke of CASA with different initial SMA wire lengths under different preload weights.

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**Supplementary Figure 6**. **Actuation displacement as a function of frequency for SMA wire with a diameter of 0.025 mm. a,** Actuation displacement of CASA under 10 Hz **b,** 20 Hz **c,** 30 Hz.



**Supplementary Figure 7.** **Performance characterization of CASA. a,** Experimental setup for measuring the actuation stroke of the CASA. **b,** Experimental setup for measuring the blocked force of CASA. **c,** Schematic of the experimental setup for measuring the actuation stroke of the CASA with additional load. **d,** Actuation stroke of pre-loaded CASA when voltage is applied. and correspond to the times of initial and equilibrium actuation, respectively. **e,** Specific power plot of pre-loaded CASA.



**Supplementary Figure 8.** **Analytic modeling** **result of CASA. a,** Force-strain curve plots of SMA and compliant beam. **b,** Vertical displacement as a function of horizontal displacement of CASA.

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**Supplementary Figure 9.** **Maximization of actuation stroke and force. a,** Serially connected CASA for maximizing actuation stroke before and after applying voltage. **b** and **c,** Front view of nondeformed (**b**) and deformed (**c**) serially connected CASA and origami linear stage using Sarrus linkage. (left) Schematic of the serially connected CASA embedded in the linear stage. (inset) Isometric-view optical image for exhibiting the serially connected CASA in the stage. **d,** (left) Illustrations of the CASA with additional lines of the SMA wire for amplifying the actuation force. (right) Front view of the operational image of the CASA-amplifying force. **e** and **f,** Actuation image of the CASA-amplifying force with a 300 g load.



**Supplementary Figure 10.** **Fabrication of CASA and BPS in actuator module for AR glass devices. a,** Optical image and exploded-view schematic illustration of a linear actuator module for optical actuation component. **b,** Optical image of the OLED display. **c,** Top-view optical image of BPS and CASA before assembly. **d,** Fabrication procedure for inducing bi-stability of the BPS. **e,** Two stable states of the BPS with an external frame. **f,** Actuation with state transition from 1 to 2 by embedded CASA (green line) and 2 to 1 by the counter SMA actuator (diagonal).



**Supplementary Figure 11.** **Performance characterization of BPS. a,** Experimental setup for measuring the reaction force of BPS. **b,** Sample experimental measurement (0.1 Hz) in Fig. 3F of actuation stroke and input voltage of the CASA with and without BPS. **c,** Blocked force plot of CASA with one line of embedded SMA wire. **d,** Input energy () plots for comparison between CASA with (red) and without (black) BPS, while changing the actuation frequency from 0.1 to 1.25 Hz for 20 s.



**Supplementary Figure 12. Direct display switching due to CASA and 3D image rendering. a,** VAC in a conventional 3D stereoscopic display. **b,** VAC reduction performed by direct display switching using CASA. **c,** Experimental data of image depth switching according to CASA operation. Negative sign of image distance means that the image is virtual because the display is located within the focal length of the curved mirror. **d,** Left and right images for binocular parallax at near/far depth. **e,** Magnification correction for 3D image-rendering method corresponding to change of depth. The default FoV of the AR prototype is determined by the optical power. The nonlinear change of the image magnification was measured through the experiments, and the distortion of the image was corrected by reflecting it in 3D rendering. 3D rendering is performed by determining the FoV of the camera or the corrected camera depth by adding a magnification correction value to the camera position value according to the floating depth of the image.

**Supplementary** **Table 1. Parameters for the design of CASA.**

|  |  |  |
| --- | --- | --- |
| Parameter | Symbol | Value |
| Mass of CASA |  | g |
| Length of the beam |  | 12.5 mm |
| Characteristic radius factor |  | 0.8156 |
| Length of a row of SMA wire |  | 22.85 mm, 23.2 mm,  23.55 mm, 23.9 mm,  24.25 mm |
| stiffness coefficient of the beam |  | 2.566 |
| Flexural modulus of the beam |  | 9.5 GPa |
| moment of inertia of the beam |  | 0.0089 mm4 |
| cross-sectional area of the SMA wire | A | 0.008107 mm2 |
| Austenite young's Modulus |  | 40 GPa |
| Martensite young's Modulus |  | 11.5 GPa |
| Residual strain |  | 0.0355 |
| Critical strain |  | 0.055 |

**Supplementary** **Table 2. Comparison of variable amplification structure.**

|  |  |  |
| --- | --- | --- |
|  | Strain | Force |
| Normal bias spring | 3 % | High |
| Dead Weight bias | 4 % | High |
| **CASA  (Compliant beam bias)** | **56 %** | **High** |
| Right angle pull | 14 % | Low |
| Simple lever (6:1 ex) | 40 % | Low |

**Supplementary** **Table 3. Data sheet of the SMA wires.**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Diameter Size (mm) | Resistance per unit length (Ohm/m) | Heating  pull force (mN) | Cooling deformation force  (mN) | Approximate current for 1 second contraction (mA) | Cooling time @ 90 ℃ (seconds) |
| 0.025 (1 mil) | 1425 | 87.2 | 35.3 | 45 | 0.15 |
| 0.050 (2 mil) | 500 | 352.8 | 137.2 | 85 | 0.3 |
| 0.10 (4 mil) | 126 | 1401.4 | 558.6 | 200 | 0.9 |

**Supplementary** **Table 4. Parameters for the design of BPS.**

|  |  |  |
| --- | --- | --- |
| Parameter | Symbol | Value |
| Mass of BPS |  |  |
| Width of buckling beam |  |  |
| Length of buckling beam |  |  |
| Thickness of SUS 304 |  |  |
| Width of parallelogram hinge |  |  |
| Length of parallelogram hinge |  |  |
| Width of parallelogram hinge |  |  |
| Contraction length of bucking beam |  |  |
| Young’s modulus of SUS 304 |  |  |
| Elastic beam stiffness of BPS |  |  |
| Parallelogram structure stiffness |  |  |

**Supplementary Video 1**

**Adjusting depth of virtual image with depth switching module**

This video shows that depth switching module in AR glasses adjusts the depth of virtual image (turtle) between far (0.2 D) and near (3.3 D) focus. Camera focus of part 1 is fixed at the far plane. When CASAs in AR glasses are undeformed, a depth of the virtual image is far. The virtual image is clear because the virtual focus and the camera focus are matched. When CASAs in AR glasses are deformed, virtual object is changed to blurred image. This blurred image is due to the difference of the camera focus and virtual image depth. The depth of the virtual image is also altered between near and far in near camera focus.

**Supplementary Video 2**

**High-power actuation of CASA in thin and light haptic glove**

This video describes the whole characteristics of the CASA which are the light weight, thin form factor, compliant structure, amplified-strain actuation and high power density of the CASA. The hand can freely grip and move with multiple number of CASAs embedded in the thin latex glove. The CASAs are able to throw 10 g of weight high in the air.

**Supplementary Video 3**

**Actuation of CASA**

This video shows actuation and performance of CASAs. It describes actuation of optimized design of CASA and its components which are compliant beams, SMA wire, and crimps. CASA of 0.22 g can lift up preload of 80 g and show high speed actuation performance. CASA can be also designed at small scale.

**Supplementary Video 4**

**High-speed actuation of CASA**

This video shows high-speed actuation of CASAs. It shows that CASA can be designed thinner than the smartphone and actuate at high power to throw the table tennis ball and pendulum. Under high preload we measured the maximum power density of the CASA.

**Supplementary Video 5**

**Actuation of CASA with BPS**

This video describes transition mechanism of BPS between the two stable state and shows actuation mechanism of CASA with BPS at 0.5 Hz and 1 Hz. Actuated CASA pushes centerline of moving platform of BPS. When the energy induced by CASA exceed threshold energy () of bistable structure, the state of BPS is switched from state 1 to 2. To shift the state from 2 to 1, a counter SMA wire is employed. This SMA wire pulls moving platform. Similarly, the state of BPS is switched from 2 to 1 by induced energy of counter SMA wire.

**Supplementary Video 6**

**Actuation of depth switching module in AR glasses**

This video shows utilization of CASA and CASA with BPS as depth switching module in AR glasses prototype. The two-depth switching module pushes the OLED display panel toward curved mirror. When the OLED display panel is close to the curved mirror, the virtual image is at near depth. On the contrary, when display panel is far from the curved mirror, the virtual image is at far depth. Part 2 and 3 show actuations of CASA with and without BPS in AR glasses.

**Supplementary Video 7**

**CASA in transparent haptic glove for visualization**

The scalable CASAs are embedded in the wearable haptic glove. This video describes realizing tactile sensation by interaction between human skin and wearable haptic glove. Part 1 shows actuation mechanism of CASA in haptic glove and actuation of CASA in a fingertip. Part 2 shows simultaneous actuation of all CASAs in fingertip and palm of human hand.

**Supplementary Video 8**

**Scaling up actuation stroke of CASA**

This video shows serial connected CASA and its scaling up actuation stroke. Part 2 shows actuating origami linear stage (Sarrus linkage) by using serial connected CASA without load. Part 3 shows actuating origami linear stage by this actuator under 60 g load.

**Supplementary Video 9**

**Scaling up actuation force of CASA**

This video shows compact arrays of SMA wire in CASA to scale up actuation force. As shown in part 1, actuation stroke of this actuator is similar to CASA with two lines of SMA wire. However, this force-amplified CASA can lift approximately 800 times heavier weight (300 g) than its own weight as shown in part 2.