2023 IEEE International Conference on Robotics and Automation (ICRA 2023)
May 29 - June 2, 2023. London, UK

A Plug-In Weight-Shifting Module That Adds Emotional Expressiveness to Inanimate Objects in Handheld Interaction

Yohei Noguchi
University of Tsukuba
Tsukuba, Japan
noguchi@ftl.iit.tsukuba.ac.jp

Yijie Guo
University of Tsukuba
Tsukuba, Japan
guo@ftl.iit.tsukuba.ac.jp

Fumihide Tanaka
University of Tsukuba
Tsukuba, Japan
fumihide.tanaka@gmail.com

***Abstract*—A plug-in weight-shifting module that can be inserted into a variety of objects is presented. The module is equipped with a movable weight inside its body. Three-dimensional weight shifts are presented by controlling one-dimensional translational and two-dimensional rotational movements. To explore the use case of this weight-shifting module, eight weight shift patterns expressing certain emotions were created through a workshop and a qualitative analysis. User tests, to which three different embodiments and scenarios were applied, examined the following three cases: the weight shift patterns were presented to the user by a) a stuffed toy-style robot that mediated human messaging, b) a cushion that made the user relax, and c) a container that enhanced the user's movie-watching experience. User interviews revealed the feasibility of the module and its weight shift patterns for the user's perception of emotions.**

***Index Terms*—robot/agent expression, weight-shifting, emotion, sketch-drawing, OMOY-3D.**

I. INTRODUCTION

Haptic interaction is becoming an important channel in human-robot interaction (HRI). Studies demonstrated that haptic HRI influences human task performance [1], emotional perception [2], [3], and building relationships [4], [5]. Commercial robots also introduce haptic interaction capabilities, enabling them to perform emotional interactions with the user. For example, LOVOT [6] is a companion robot having touch sensors over its body and is designed to react accordingly to human touch.

In this paper, we discuss the use of an internal weight movement, namely, weight-shifting, for the purpose of haptic HRI. In this approach, a movable weight is embedded inside the body of the robot and moved by specific mechanical components. Consequently, the robot can express its emotions or other internal states through the weight-shifting to the user who holds it. In addition, in contrast to the typical physical HRI using a robot moving its arms or legs [7], the risk of the user's injury can be reduced because the movable weight as well as its actuators are totally covered with the exterior. The original idea of such a weight-shifting was introduced in [8] by investigating two-dimensional (2D) weight movements in a single-shape small robot. However, the movement patterns were limited on a 2D plane, and because its mechanical components were fully embedded in the robot, its applicability was also limited. To address these limitations, we developed a new mechanical module, called OMOY-3D, which can render three-dimensional (3D) weight shift patterns in handheld interaction (Fig. 1). A 350 gram of tungsten weight was attached to an internal mechanism that enabled the weight to move around according to a 3D polar coordinate. We adopted a "plug-in" design to allow it to be inserted into a variety of objects (i.e., existing robots and objects, such as stuffed toys or cushions). See Fig. 2 showing the OMOY-3D with different embodiments.

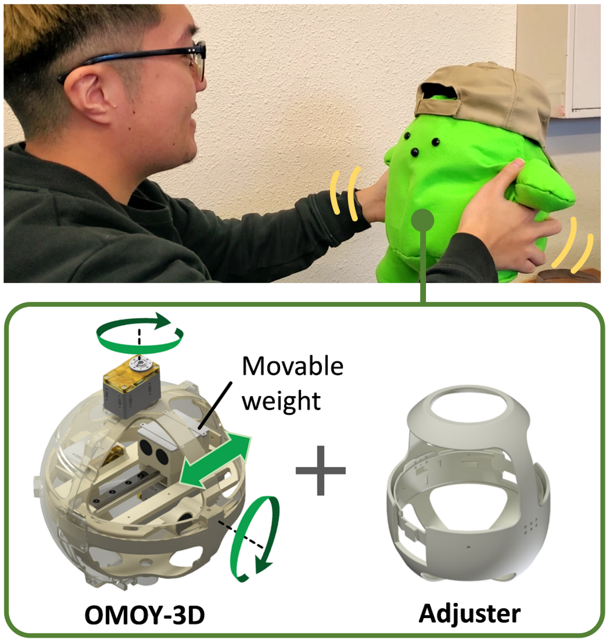


Fig. 1. An embodiment (stuffed toy-style) of the OMOY-3D module that is plugged in by using an adjuster. The module is equipped with a movable weight that is controlled by a translational and two rotational mechanisms, thus rendering 3D patterns of weight-shifting. The stuffed toy robot provides the user with weight-shifting movements along with speech.

This work was supported by JSPS KAKENHI Grant Number 20J10887, 20H05553 and 22H04856.

Fig. 2. Three variations of OMOY-3D embodiments (left: a stuffed toy-style / center: a cushion-style / right: a container-style).

However, a big issue here is that there is no design methodology to create 3D weight-shifting movements for this module. To address this issue, we conducted a study to design effective patterns for expressing emotions that can be useful in different contexts. To this end, we first collected 48 draft ideas of weight shift patterns from a sketch-drawing workshop. Then, by qualitatively analyzing these sketches, we obtained eight weight shift pattern designs to express certain emotions based on the theory of the Laban Movement Analysis (LMA) [9].

To explore the feasibility of these designed patterns, we implemented the patterns in OMOY-3D and tested them by five participants. We introduced three different embodiments with specific scenarios, where the weight shift patterns were presented to the user by a) a stuffed toy-style robot that mediated human messaging, b) a cushion-style robot that made the user relax, and c) a container-style robot that enhanced the user's movie watching experience. Although the number of participants was small, we obtained useful feedback from this test to discuss the feasibility and the applicability of the module presented, and therefore we will report those results in this paper.

To summarize, the contribution of this paper is as follows:

- The mechanical design of a 3D weight-shifting module (OMOY-3D) that can be plugged into a variety of objects.
- The design and the implementation of 3D weight-shifting movements expressing emotions.
- Results from a pilot test discussing the feasibility and the applicability of the OMOY-3D.

II. RELATED WORK

Handheld devices having weight-shifting functions have been mainly explored in the virtual reality (VR) research field. Since Woodruff and Helson [10] found the relationship between the presented torque and the human perception of heaviness in 1965, researchers have been adopting this phenomenon in designing weight-shifting devices [11]–[14]. These works demonstrated that the virtual perception of objects can be well enhanced by changing the weight distribution. Compared to these previous works, the novelty of the present study stands in exploring emotional expressions by introducing 3D weight-shifting. We also focus on providing the weight-shifting sensory during interaction with inanimate physical (not virtual) objects.

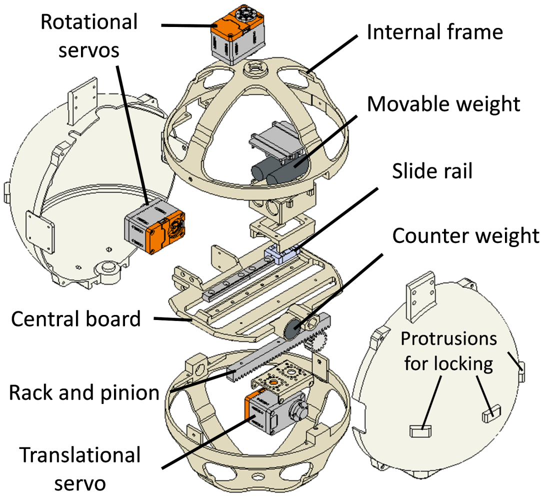


Fig. 3. Hardware specification of OMOY-3D: 350 gram tungsten weight is attached to 1D translational and 2D rotational (vertical/horizontal) mechanism. This allows the weight to move spatially on a 3D polar coordinate system. 50 gram weight is attached at the opposite side of the motor to compensate for horizontal motor mass.

Emotion expression is a major topic in robotics research. Many social robots have been designed to convey emotional states using verbal and/or non-verbal channels, such as facial expressions [15], body movements [16], sounds [17], sweats [18], colors [19], vibrations [20], and their combinations [20], [21]. Haptic elements, such as skin temperature [3], [22], [23], texture [2], and SwarmHaptics [24] have also been discussed. However, no work except [8] exists concerning the use of weight-shifting for the purpose of emotion expression.

III. HARDWARE DESIGN

This section explains a 3D weight-shifting module, called OMOY-3D, which can be inserted to a variety of objects. We particularly focus on three different types of embodiments (a stuffed toy, a cushion, and a container) to which weight-shifting is applied. OMOY-3D is fixed to the inside of each embodiment using the corresponding adjusters.

A. Weight-Shifting Mechanism

Fig. 3 illustrates the hardware specification of OMOY-3D. Most parts were 3D printed using ABS or ASA materials. The exterior formed a regular sphere with 188 mm diameter, while 350 gram of tungsten weight was implemented inside. The weight was attached to a translational and two rotational mechanisms, such that the weight can spatially move on a 3D polar coordinate system.

For the translation mechanism, we applied a pair of rack and pinion gear. The pinion gear was connected to a Dynamixel XC430-W150T servo motor (1.6 Nm at a 12 V with 1.4 A) and conveyed its torque to the rack. The rack was 130 mm long. The tungsten weight can be moved linearly for each gear pitch of 3.82 mm. A linear guide rail was inserted between the weight and a central board to smoothen the movement. The total weight of the part assembly moved by the translation mechanism was 479 gram.

For the rotation mechanisms, a Dynamixel XC430-W150T servo motor was installed on each vertical and horizontal axis. The motor on the vertical axis was fixed to the exterior of OMOY-3D and conveyed its torque to the internal frame, while that on the horizontal axis was fixed to the internal frame and conveyed its torque to the central board. 50 gram weight was attached at the opposite side of the motor to compensate for horizontal motor mass.

B. Plug-in Function

A mechanical locking function was implemented to enable the module plug-in. Six protrusions were placed on the exterior of the prototype. Fixing becomes possible by matching them to a certain position of the adjuster. This section describes how three different embodiments (a stuffed toy, a cushion, and a container) are applied to OMOY-3D.

1) Installation to a Stuffed Toy: The stuffed toy shown in Fig. 2 (left) was made of felt fabric. Its eyes and nose were represented by glossy black buttons. Inside the cap, there was a space for fixing a motor-controlling board. OMOY-3D should be able to be applied to any kind of stuffed toys of similar size. Here, we fabricated it by ourselves to avoid copyright issues. For the installation, the protrusions on OMOY-3D surface were first inserted into the grooves of the adjuster. Next, OMOY-3D was rotated 30° inside the adjuster to lock and then installed to the stuffed toy. The size and the total weight, including OMOY-3D, were approximately H: 295 mm, W: 250 mm, D: 220 mm, 1,866 gram, respectively.

2) Installation to a Cushion: The appearance of a cushion used in this study is shown in Fig. 2 (center). We fabricated the adjuster using two boards of vinyl chloride resin and four pieces of 3D printed parts. The core unit was sandwiched with those parts and put into a commercially available cushion cover (45 cm × 45 cm). Four bags filled with small spheres made of styrene foam were inserted to give the sensory of softness to the user. The total weight, including OMOY-3D, was approximately 2,004 gram.

3) Installation to a Container: The container-style embodiment shown in Fig. 2 (right) was designed for use as a vessel for popcorn. It was made of thick papers with a unique pattern to fit this context. A 3D printed adjuster with a groove to lock the OMOY-3D was placed on the bottom of the container. The embodiment measured H: 250 mm, W/D: 240 mm. The total weight was approximately 1,533 gram.

IV. 3D WEIGHT-SHIFTING DESIGN

Designing a 3D weight shift movement is not trivial and no formal design methodology exists for creating it for OMOY-3D. To address this issue, we conducted an exploratory design trial that consisted of the three phases explained in this section.

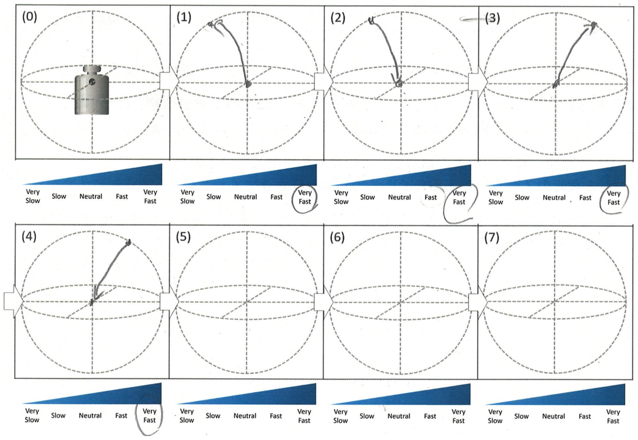


Fig. 4. An example of a draft idea about a 3D weight shift pattern drawn by a male participant in the sketch-drawing workshop. This sketch represents his excited emotional state in the moment he watched the trailer of a video game. The weight was "jumping up," moving to the right/left and forward/backward in the sphere.

A. Sketch-drawing Workshop

A workshop was held with six participants (three males and three females ages 21–25 years) to collect draft ideas for the 3D weight shift patterns.

At the beginning of the workshop, the participants were asked to remember recent events related to each of the following eight emotions: *excited, happy, relaxed, sleepy, bored, sad, annoyed, and afraid*[1]. They were then asked to draw weight movements representing each emotion they had in their mind. Fig. 4 illustrates a sample sketch drawn by a participant. The gray-lined spheres indicate the area in which the weight can move. Each blank was arranged in a time-sequential manner. Therefore, participants drew important weight movements in each blank as if they were making a few-frame animation. For each frame, they were asked to choose a proper speed based on a five-point scale of 1: very slow to 5: very fast. Very slow (21 rpm) and very fast (105 rpm) translational weight movements had been presented to each participant by using OMOY-3D to provide a reference for the physical sensation of weight shifting. In addition, we supplemented each sketch by asking participants for a detailed explanation of their design concept and the geometric shape of each motion sketch.

B. Sketch Analysis

48 sketches (six collaborators, eight emotions) and their design concepts were collected. A qualitative analysis was performed to utilize the data collected from the workshop in designing the 3D weight shift patterns. In addition to the collected design concepts, we considered movement features involved in each sketch. Each sketch was given codes describing its movement features based on the Laban-Movement Analysis (LMA) [9] and its Effort and Shape components. This section explains the coding procedure.

---

[1] Those emotions were selected from Russel's Circumplex model of affect [25] and cover all four quadrants in this emotional model.

TABLE I
LABELS AND CODING CRITERIA FOR MOTION FACTORS.

	Label name	Coding criteria
Weight	Light	If the average speed is ≤ 2.
	A little light	If the average speed is $> 2, \leq 3$.
	A little strong	If the average speed is $> 3, \leq 4$.
	Strong	If the average speed is > 4.
Space	Direct	If straight paths are mainly used.
	Indirect (curve)	If curved paths are mainly used.
	Indirect (wave)	If waved paths are mainly used.
	Others	The other cases.
Time	Sustained	If the speed is constant.
	Intermediate	If there is a speed difference (< 3) between adjacent keyframes.
	Sudden	If there is a speed difference (≥ 3) between adjacent keyframes.
Horizontal	Spreading	If the weight moves to the left and right evenly.
	Enclosing	If there is no horizontal movement.
	Others (partial)	If the weight moves only to the left or right.
Vertical	Rising	If the weight moves mainly on the upper side of the sphere.
	Sinking	If the weight moves mainly on the bottom side of the sphere.
	Others (evenly)	If the weight moves to the up and down evenly.
	Others (none)	If there is no vertical movement.
Sagittal	Advancing	If the weight moves mainly on the front side of the sphere.
	Retreating	If the weight moves mainly on the back side of the sphere.
	Others (evenly)	If the weight moves back and forth evenly.
	Others (none)	If there is no sagittal movement.
Repetition	Repetitive	If there is a repetitive element.
	Single	No repetition.

We interpreted *weight*, *space*, and *time* elements involved in the Effort component as “the average speed reported by participants”, “the shape of trajectories mainly used in sketch”, and “sudden acceleration or deceleration”. The Shape component was interpreted as “a region in the sphere used in the sketch”. The *horizontal*, *vertical*, and *sagittal* aspects of the sphere were considered. In addition to the LMA components, a repetition factor, which was known to have a relationship with the intentional movement design [26], was also considered.

We prepared a set of labels and coding criteria for the above-mentioned motion factors (TABLE I) while referring to the terms reported in [27]. Two coders, who provided the labels to the 48 sketches one by one while making a consensus on their judgments of each other, were assigned.

C. Pattern Implementation

We designed eight weight shift patterns representing certain emotions illustrated in Fig. 5 based on the design concepts collected in the workshop and the codes described in the previous section. An OpenCR board was used to control the three Dynamixel motors that daisy-chained and communicated with the board. We programmed eight weight shift patterns on this board.

1) Trajectory: Thick dots plotted in Fig. 5 denote the positions where the weight reaches at. In the *excited* and *happy* states, the upper part of the sphere was used. Repetitions were included in these patterns where the weight moved between the origin and each point. In *relaxed* state, the weight repeatedly moved on the horizontal plane with a trajectory shown in Fig. 5. For the *sleepy*, *bored*, and *sad*, the lower part of the sphere was used. For expressing *sleepy*, the weight moved in a similar way as a head moves when a person is dozing. Consequently, a movement to express breathing was performed. In the *bored* state, the weight performed a repetitive movement like a pendulum on a vertical plane (Y-Z plane in Fig. 5). The weight vertically fell in the *sad* state. For expressing *annoyed*, the weight moved linearly on the diameter of the sphere while rotating in the range of $\pm 45^\circ$ to 90°. For the *afraid* state, vibration was designed to express trembling.

2) Speed and Acceleration: In the *excited*, *relaxed*, *sleepy*, *bored*, and *sad* states, we implemented a specific acceleration pattern to each motion design. For expressing *excited*, we designed a skipping weight by high initial velocity and gravitational acceleration. In the *relaxed* state, we implemented a motion sequence with a long deceleration section like the behavior of rippling waves. For expressing *sleepy*, *bored*, and *sad* states, a slow and a gravitational acceleration were mainly considered. Each sinking section in these patterns was designed as well. For the other emotions (i.e., *happy*, *annoyed*, and *afraid*), motion sequences with specific accelerations were not included. The weight moved at a constant speed, either fast or very fast for these emotions. For example, Fig. 6 shows a speed and acceleration design of the weight shift patterns that represents (a) *relaxed* and (b) *afraid*.

V. PILOT TEST

To explore the feasibility and the applicability of the OMOY-3D module and designed weight shift patterns, we conducted a pilot test. Three different interaction scenarios were used and weight-shifting was presented during the interaction. Five participants (three males and two females aged 18–26 years) were recruited[2], and they all participated in the three scenarios. An experimenter sat in front of the participant and collected feedback through semi-structured interviews. The test was videotaped and used in the analysis.

A. Interaction with Stuffed Toy-style Robot

1) Methods: The stuffed toy-style embodiment and eight weight shift patterns were used. We introduced herein a scenario to participants in which “a stuffed toy-style robot reads out a text message received from a friend.” by using its voice synthesis function. Mediating human messaging is a promising application of social robot [28]. The emotional elements of a message are expected to be enhanced if the robot performs weight-shifting during the messaging interaction.

We created a set of daily text messages for this pilot test. First, we made multiple text messages as candidates based on the discussion with the workshop participants. At least two candidates were made for each emotion. We then conducted an online survey with seven participants, who are different from the participants recruited for this pilot test to select the one which can be easily associated with each emotion. For each candidate, the participants were asked “According to the

---

[2] The study protocol was approved by the research ethics committee of the Faculty of Engineering, Information, and Systems in University of Tsukuba. All participants provided informed consent.

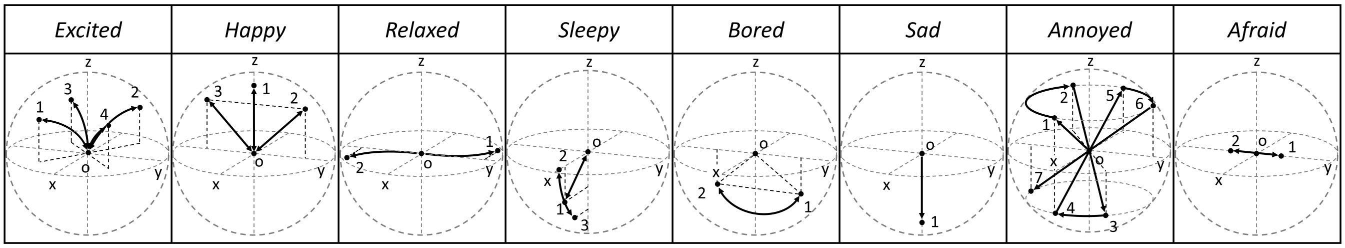
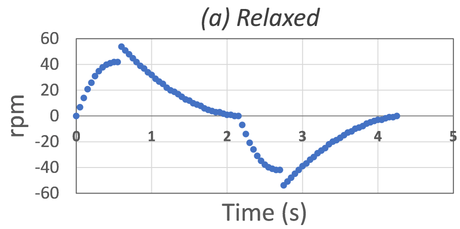


Fig. 5. Trajectories of 3D weight shift patterns designed in this study.



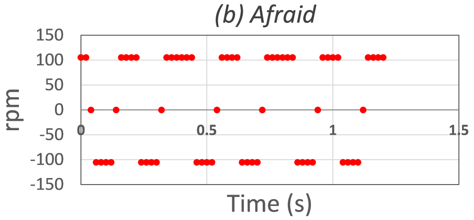


Fig. 6. Speed and acceleration design of the weight shift patterns expressing (a) relaxed and (b) afraid. Each point indicates the RPM value of the translational servo.

TABLE II
TEXT MESSAGES SPOKEN BY THE STUFFED TOY ROBOT.

Emotion	Text messages
Excited	I'm in Ueno. I'm excited every time I come here.
Happy	Colleagues gave me a surprise on my birthday. The cake with lots of fruit was delicious.
Relaxed	I'm relaxing at a footbath. It's warm and comfortable.
Sleepy	I'm full. Once I sit on a chair, I'll fall into a sleep.
Bored	I'm at an office for my part-time job, but it's boring because there is nothing to do and no customer.
Sad	My parents' cat ignored me. He is mean.
Annoyed	When I was singing at a karaoke room with my friends, a strange drunk man came into the room. It was annoying.
Afraid	I heard that a suspicious person is wandering around in our neighborhood.

sentence, which is the closest to the emotion that the sender is trying to convey?" The question had eight forced-choice options (excited / happy / relaxed / sleepy / bored / sad / annoyed / afraid). As a result, text messages having the highest agreements among the emotion perception of the participants were determined (TABLE II). Then, we created audio clips for the robot speech. A text-to-speech API provided by NTT Docomo was used for the voice synthesis[3].

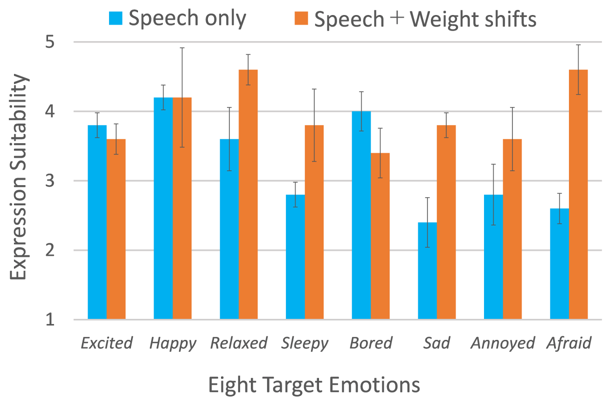


Fig. 7. Perceived suitability for each emotion expression (speech only / speech + weight-shifting) during the interaction with a stuffed toy-style robot. Error bars are 1.0 SEM.

2) Procedure: Only the speech factor of the robot was tested in the first half of each session. Participants were asked to hold the robot. The audio clip was played using a small speaker attached inside its body. For each audio clip, the participants were asked to evaluate whether the robot's voice was suitable to convey emotional content of the message. A five-point scale of "1: not suitable" to "5: suitable" was used for the evaluation.

Then, the combination of speech and weight-shifting was tested in the second half of the session. The robot read the message while presenting the corresponding weight shift pattern. For each robot expression (speech + weight-shifting), participants were asked to evaluate its suitability based on the five-point scale. In addition, for each expression, the participants were asked in an open-ended question to describe their impression on the presented weight shift, detailing what feature caused that impression.

3) User Feedback and Discussion: Fig. 7 shows the average scores of the perceived suitability for each emotion expression. Overall, participants reported acceptable suitability to the robot presenting weight-shifting when it delivered messages. Relatively large differences were observed between the speech only condition and the speech + weight-shifting condition in the *relaxed*, *sleepy*, *sad*, *annoyed*, and *afraid* states. In this scenario, the created 3D weight shift patterns may be particularly effective for expressing these emotions.

---

[3] The robot spoke with a neutral speed, pitch, and emotion.

Concerning the *bored* state where participants' evaluation for the weight-shifting condition was not good, a participant mentioned "Although the speed design was good, it moved too much. That is, for expressing *bored*, the weight movement should be smaller." Thus, it may be important to design the length of the trajectories shorter or reduce the number of motors to be activated to improve the *bored* expression. In the *excited* and *happy* states, we did not find a clear difference between the two conditions. Three participants commented that the robot voice fit very well to this scenario context and it had already shown nice suitability.

A further research question arose here considering the interaction effect between speech and weight-shifting: how will the human perception of emotions be affected by the combination of the speech type of robot and the weight shift pattern? HRI researchers have been reporting that the combination of haptic sensations and other expression modalities has a unique effect on the user's perception of emotions. For example, [3] showed that in haptic interaction with social robot, there were combinations where thermal haptic expression predominated over facial expression in the user's perception of the robot's emotional states. Exploring this research question will help the design of a weight shift pattern for the situation where the robot wants to express complex emotional states.

B. Interaction with Cushion-style Robot

1) Methods: The cushion-style embodiment and the weight shift pattern representing *relaxed* were used. We introduced a scenario to participants in which they got relaxed with a cushion during a break. The cushion presented the weight shift pattern while being hugged by the participants. In this setting, the participants were asked for their opinions through semi-structured interviews: "Frankly what did you think of the weight movement?", "Do you think is it possible to get relaxed by the presented weight movement?", and "What feature do you think needs to be improved to make you more relaxed?"

2) User Feedback and Discussion: Two participants mentioned that they thought it was possible to relax using the cushion robot with weight shifts. On the contrary, the other three participants were skeptical on this effect. However, most of their comments suggested that the exhibiting weight-shifting could increase or continue their motivations to hold the cushion. For instance, a participant commented that "I think this cushion can be held for a long time. I often use cushions when I'm lonely, but this cushion robot gives me a sense as if it is living and makes me want to use it often." In conclusion, applying OMOY-3D to the cushion-style embodiment can be possible; however, further improvement and investigation is needed to identify clearer merits for this scenario.

C. Interaction with Container-style Robot

1) Methods: The container-style embodiment and the weight shift pattern representing *afraid* were used. We introduced a scenario to participants in which they were watching a movie while eating popcorn. The participants were asked to watch a horror movie clip for approximately 7 min while holding the container. During the movie, the experimenter sent a command to the robot to exhibit the weight shift pattern in predefined moments (e.g., the title of the movie appeared and a hero in the movie found a ghost). The weight shift pattern was presented to each participant four times. After watching the video, participants were interviewed about their opinions to the following questions: "Frankly speaking, what did you think of the weight movement?", "Do you think is it possible to enhance the movie watching experiences by the weight movements?", and "What feature do you think needs to be improved to make the experience better?"

2) User Feedback and Discussion: Through the interview, four participants reported that the robot and its weight-shifting contributed to enhancement of their movie watching experience. They commented "it aroused my disquieting feeling", "it brought out surprises and enhanced", and "it was fun as if I was watching a 4DX movie". Judging from those comments, the weight shift pattern used in this scenario seems to be feasible. However, a participant had a totally negative opinion because a slight but certain preliminary motion of the weight shift pattern bothered his concentration to the movie. This comment indicates that it is important to design the speed and acceleration of the preliminary motions smaller to avoid distracting the user.

VI. LIMITATIONS AND FUTURE WORKS

The current OMOY-3D wires (connected to the three Dynamixel motors) obstruct continuous rotations along the vertical and horizontal axes. The rotation angles of all created weight shift patterns were designed between 0° to 360°. Fully wireless designs are needed to enable the implementation of more flexible patterns than the current state.

Multiple participants mentioned that motor sounds were a little distracting. Servo noises, particularly in the patterns expressing *annoyed*, were also pointed out. However, interestingly, for a servo noise at the pattern for expressing *relaxed*, some participants mentioned that the noise was comfortable (i.e., recognized as sounds like waves at the seacoast). Investigating the effect of servo noises would be an interesting research topic.

Follow-up studies are necessary to confirm the scalability of our preliminary findings. Particularly, empirical studies having a larger number of participants are needed to identify the exact effects of 3D weight-shifting and its factor details.

VII. CONCLUSION

In this paper, we presented the basic concept and the implementation of the OMOY-3D module that can add emotional expressiveness to inanimate objects. We also reported the design process of eight 3D weight shift patterns through a workshop and a qualitative analysis based on the LMA. Preliminary findings from a pilot test showed the feasibility of the concept, although, depending on the use case, participants reported mixed comments, suggesting needs for further studies.

REFERENCES

[1] M. Shiomi, K. Nakagawa, K. Shinozawa, R. Matsumura, H. Ishiguro, and N. Hagita, "Does A Robot's Touch Encourage Human Effort?" *International Journal of Social Robotics*, vol. 9, pp. 5–15, 2017.

[2] Y. Hu and G. Hoffman, "Using Skin Texture Change to Design Emotion Expression in Social Robots," in *Proceedings of the 14th ACM/IEEE International Conference on Human-Robot Interaction*. IEEE, 2019, pp. 2–10.

[3] D. Peña and F. Tanaka, "Human Perception of Social Robot's Emotional States via Facial and Thermal Expressions," *ACM Transactions on Human-Robot Interaction*, vol. 9, no. 4, 2020, paper 26.

[4] C. D. Kidd, W. Taggart, and S. Turkle, "A Sociable Robot to Encourage Social Interaction among the Elderly," in *Proceedings of the 2006 IEEE International Conference on Robotics and Automation*. IEEE, 2006, pp. 3972–3976.

[5] C. J. A. M. Willemse and J. B. F. van Erp, "Social Touch in Human–Robot Interaction: Robot-Initiated Touches can Induce Positive Responses without Extensive Prior Bonding," *International Journal of Social Robotics*, vol. 11, pp. 285–304, 2018.

[6] (2018) The LOVOT website. [Online]. Available: https://lovot.life/en/

[7] A. D. Santis, B. Siciliano, A. D. Luca, and A. Bicchi, "An atlas of physical human–robot interaction," *Mechanism and Machine Theory*, vol. 43, no. 3, pp. 253–270, 2008.

[8] Y. Noguchi and F. Tanaka, "OMOY: A Handheld Robotic Gadget That Shifts Its Weight to Express Emotions and Intentions," in *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. ACM, 2020, paper 646.

[9] R. Laban, *The Mastery of Movement*. Plays, Inc., Boston, 1971.

[10] B. Woodruff and H. Helson, "Torque: A New Dimension in Tactile-Kinesthetic Sensitivity," *The American Journal of Psychology*, vol. 78, no. 2, pp. 271–277, 1965.

[11] C. Swindells, A. Unden, and T. Sang, "TorqueBAR: An Ungrounded Haptic Feedback Device," in *Proceedings of the 5th International Conference on Multimodal Interfaces*. ACM, 2003, pp. 52–59.

[12] A. Zenner and A. Krüger, "Shifty: A Weight-Shifting Dynamic Passive Haptic Proxy to Enhance Object Perception in Virtual Reality," *IEEE Transactions on Visualization and Computer Graphics*, vol. 23, no. 4, pp. 1285–1294, 2017.

[13] J. Shigeyama, T. Hashimoto, S. Yoshida, T. Narumi, T. Tanikawa, and M. Hirose, "Transcalibur: A Weight Shifting Virtual Reality Controller for 2D Shape Rendering Based on Computational Perception Model," in *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. ACM, 2019, paper 11.

[14] S. Sagheb, F. W. Liu, A. Bahremand, A. Kidane, and R. LiKamWa, "SWISH: A Shifting-Weight Interface of Simulated Hydrodynamics for Haptic Perception of Virtual Fluid Vessels," in *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. ACM, 2019, pp. 751–761.

[15] T. Todo, "SEER: Simulative Emotional Expression Robot," in *Proceedings of the ACM SIGGRAPH Emerging Technologies*. ACM, 2018, paper 15.

[16] T. Nakata, T. Sato, and T. Mori, "Expression of Emotion and Intention by Robot Body Movement," in *Y. Kakazu, M. Wada, T. Sato (eds) Intelligent Autonomous System IAS-5*. IOS Press, 1998, pp. 352–359.

[17] E. Jee, Y. Cheong, C. H. Kim, D. Kwon, and H. Kobayashi, "Sound Production for the Emotional Expression of Socially Interactive Robots," in *V. Kulyukin (eds) Advances in Human-Robot Interaction*. IntechOpen, 2009, pp. 257–272.

[18] Y. Guo and F. Tanaka, "Robot That Sweats to Remind the Elderly of High-temperature," in *Companion of the 2020 ACM/IEEE International Conference on Human-Robot Interaction*. ACM, 2020, pp. 221–223.

[19] K. Terada, A. Yamauchi, and A. Ito, "Artificial Emotion Expression for a Robot by Dynamic Color Change," in *Proceedings of the 21st IEEE International Symposium on Robot and Human Interactive Communication*. IEEE, 2012, pp. 314–321.

[20] S. Song and S. Yamada, "Expressing Emotions through Color, Sound, and Vibration with an Appearance-Constrained Social Robot," in *Proceedings of the ACM/IEEE International Conference on Human-Robot Interaction*. ACM, 2017, pp. 2–11.

[21] D. Löffler, N. Schmidt, and R. Tscharn, "Multimodal Expression of Artificial Emotion in Social Robots Using Color, Motion and Sound," in *Proceedings of the ACM/IEEE International Conference on Human-Robot Interaction*. ACM, 2018, pp. 334–343.

[22] J. Nie, M. Park, A. L. Marin, and S. S. Sundar, "Can You Hold My Hand?: Physical Warmth in Human-Robot Interaction," in *Proceedings of the 7th ACM/IEEE International Conference on Human-Robot Interaction*. ACM, 2012, pp. 201–202.

[23] A. E. Block and K. J. Kuchenbecker, "Emotionally Supporting Humans Through Robot Hugs," in *Companion of the 2018 ACM/IEEE International Conference on Human-Robot Interaction*. ACM, 2018, pp. 293–294.

[24] L. H. Kim and S. Follmer, "SwarmHaptics: Haptic Display with Swarm Robots," in *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. ACM, 2019, paper 688.

[25] J. A. Russell, "A Circumplex Model of Affect," *Journal of Personality and Social Psychology*, vol. 39, no. 6, pp. 1161–1178, 1980.

[26] B. Spitler, *Make It Intentional: Harness the Power of Positive Perspectives*. Balboa Press, 2016.

[27] L. Zhao, "Synthesis and Acquisition of Laban Movement Analysis Qualitative Parameters for Communicative Gestures," Ph.D. dissertation, University of Pennsylvania, 2001.

[28] Y. Noguchi, H. Kamide, and F. Tanaka, "Personality Traits for Social Mediator Robot Encouraging Elderly Self-Disclosure on Loss Experiences," *ACM Transactions on Human-Robot Interaction*, vol. 9, no. 3, 2020, paper 17.