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A Holistic Approach in Designing Tabletop Robot's Expressivity

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Abstract— **Defining a robot's expressivity is a difficult task that requires thoughtful consideration of the potential of various robot modalities and a model of communication that humans understand. Humanoid and zoomorphic-designed robots can easily take cues from human and animals, respectively when designing their expressivity. However, a robot design that is neither human nor animal-like does not have a clear model to follow in terms of designing expressivity. Animation presents a potential model in these circumstances as animated characters in movies take various forms, sizes, shapes and styles, and are successful in defining expressivity that is widely accepted across different languages and cultures. In this paper, we discuss the development and design of the expressivity of Haru, a table top robot that is neither human nor animal-like and the application of animation expertise to the holistic treatment of the different modalities. The method maximizes animation techniques and expertise normally applied to movies to generate expressivity that is then transferred to the robot hardware. Experimental results show that the robot's expressivity generated using our method is easily understood and are preferred to the conventional approach of generating expressions.**

I. Introduction

Research in social robotics has gained a lot of traction recently partly due to the advancements in AI. Current technologies enable us to design machines with a deep understanding of human behavior including affects and human intelligence. As these technologies mature, so too does the desire to develop social robots that co-exist with humans, by building bonds and forging relationship. The future success of social robots relies on a dual system that addresses both their functional usefulness and the social/emotional experience they provide for their user. Hence, it is imperative for social robots to communicate emotions in an effective manner and the first step to achieving this is through a robot's expressivity. Human empathic responses are strongly correlated with expressivity [1][2]. The importance of expressivity cannot be understated as it impacts how well a social robot is perceived, and is why most robot architectures have various mechanisms for expression generation. Here we define expressivity as the ability for a robot to successfully communicate dynamic emotional states and intent in a social context during human-robot interactions through embodied communication.

Studies show that human perception is influenced when a robot's physical appearance is inspired by a familiar facial feature, such as the inclusion of the nose, eyelids and the mouth [3]. A robot's physical embodiment, as opposed to a remote agent, also has a direct correlation to an increase in engagement frequency and social facilitation, generating

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Fig. 1. Tabletop robot Haru

an overall positive response from the users [4]. Furthermore, humans associate emotions to moving agents with characteristic gestures, with postures of the body signalling particular emotion conditions [5]. Physical movements further reinforce emotion expression, stimulating anthropomorphic reaction from human users. It was also shown that the inclusion of sounds through vocalization impacts relationship [6][7], eliciting the use of vocalization with robots. In a completely separate study, it was shown that humans are demanding in terms of their preferences. One study found a correlation between motion parameters and attribution of affect, which suggests that humans are not just keen on the robot's mere movements but also to their details and quality [8]. It was also shown that humans are susceptible to the quality of the contents when using a display [9]. These studies highlight the complexities of designing a robot's expressivity. Clearly, there is more to expressivity than just a robot demonstrating that it is capable of generating expressions. If social robots are to co-habitate with humans, both will spend a significant amount of time together, and to be able to sustain a long-term emotional interaction with social robots, factors such as appeal, style, quality and even cultural factors have to be considered. In the end, a robot's expressiveness should bring an overall positive experience to the user.

The animation industry has been developing characters of various forms, size and shapes for many years, and even developed robot characters that people enjoy to watch. It is of great value if the approach used by the animation sector can be utilized in developing actual robots. Recently, a few research projects in social robotics have employing concepts from the animation sector in designing a robot's hardware and character [11][10]. Methods of using animation tools are also extended to control movements of simple form factor toy robots with very limited modalities [12][13]. However, to date, there is no research work that employs animation techniques as extensive as our approach. In this paper, we discuss a holistic approach to designing an expressive tabletop robot named Haru [14] that is neither human-like nor zoomorphic shown in Fig. 1. We adopted techniques in

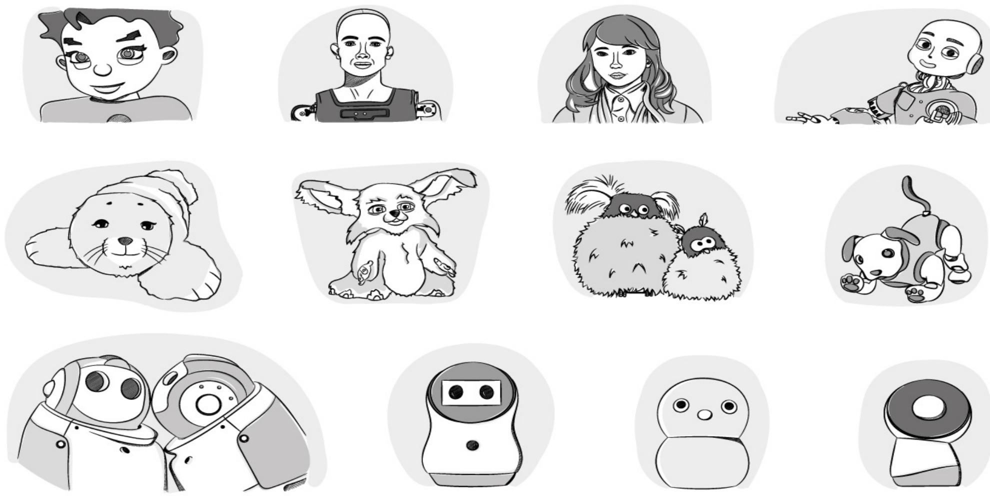

Fig. 2. Robot hardware that can physically express emotion (Artitst's rendition). From left to right, (Top: human-like expressivess; Middle: animal-like expressiveness; Bottom: robot designs that are neither human-like nor zoomorphic in which the tabletop robot falls under)

animation to combine several modalities in the design of the robot's expressivity using animation expertise. In section II, we present the background followed by the hardware, in section III. Animation expertise applied to the tabletop robot is presented in section IV, and we discuss the transfer of animated expressions to the hardware in section V. We show the evaluation in section VI and we conclude the paper in section VII.

II. Background

Fig. 2 depicts a list of robots capable of generating expressions categorized into human-like (top), animal-like (middle) and those that are neither human-like nor animal-like (bottom). The top figure (left-to-right), shows Zeno and Sophia from Hanson robotics that are equipped with actuators for facial muscle expressions [15]. Another human-like expressive female android with a natural TTS voice, is Erica [16]. Lastly, A smaller robot iCub that resembles a 3.5 year-old child compensates its lack in facial muscle expressions with several motors to control bodily movements and LED lights in the face [17].

Robots in the animal-like category are shown in the middle figure (left-to-right). Paro is a cuddly stuff toy baby seal robot, utilized for therapeutic purposes [18]. Another cuddly robot is Leonardo which is cosmetically designed to have an organic appearance [19]. Likewise, an expressive robot named Tofu, equipped with several expressions and animacy capabilities is developed for kids to play and interact with [20]. Then, the appealing robotic dog Aibo from Sony [21] which is fitted with various actuators for the mouth, head, legs, ear and tail for expressive movements.

Robots that are neither human-like nor animal like are shown in the bottom figure. The robot, PaPero was developed with cute appearance for specialized expressiveness [22]. PaPeRo expresses its character through movements and some visualization through LED illumination. Another robot thats doubles like a personal assistant is the Hub from LG [23]. It combines sounds and movements for expressive motions. A simplistic rubbery robot with expressive movements is Keepon from the National Institute of Information and Communication [24]. Lastly is Jibo, pitched as a family robot with a design inspired from animation [25].

A number of architectures have been proposed to model expressivity of an agent [26] [27] , and to some extent, these are inspired by developmental psychology. However, most of these architectures are either very limited in scope such as modeling only the facial features and do not completely take into account other modalities. In addition, the models are usually adopted from human-like (i.e. human facial expressions) or animal-like expressions. These models may not work with robots that are neither human-like nor animal-like (i.e. tabletop robot Haru), hence we adopted the animation expertise to model an animation-like character.

III. Table top Robot Hardware

The schematic diagram of the tabletop robot hardware is shown in Fig. 3. The robot is composed of the *body*, *neck* and the *eyes*. The body is a spherical volume with a diameter of 220 mm which houses all the servo motors and the addressable LED matrix display for mouth expressions among others. The robot's *neck* is approximately 143 mm in height while the eyes are composed of a 95.5 mm x 95.5 mm x 61.19 mm volumetric shell with a movable inner eye.

A. Actuation and movements

- Body Rotation
  The robot's body pivots at the base which is made of steel to lower the center of mass. Body can pan for a maximum 320 deg angle. As the body moves, the neck and the eyes move along and can be associated with azimuthal gazing
- Neck Leaning Forward and Backwards
  The robot's neck can lean forward and backward with a maximum displacement angle of 57 deg.

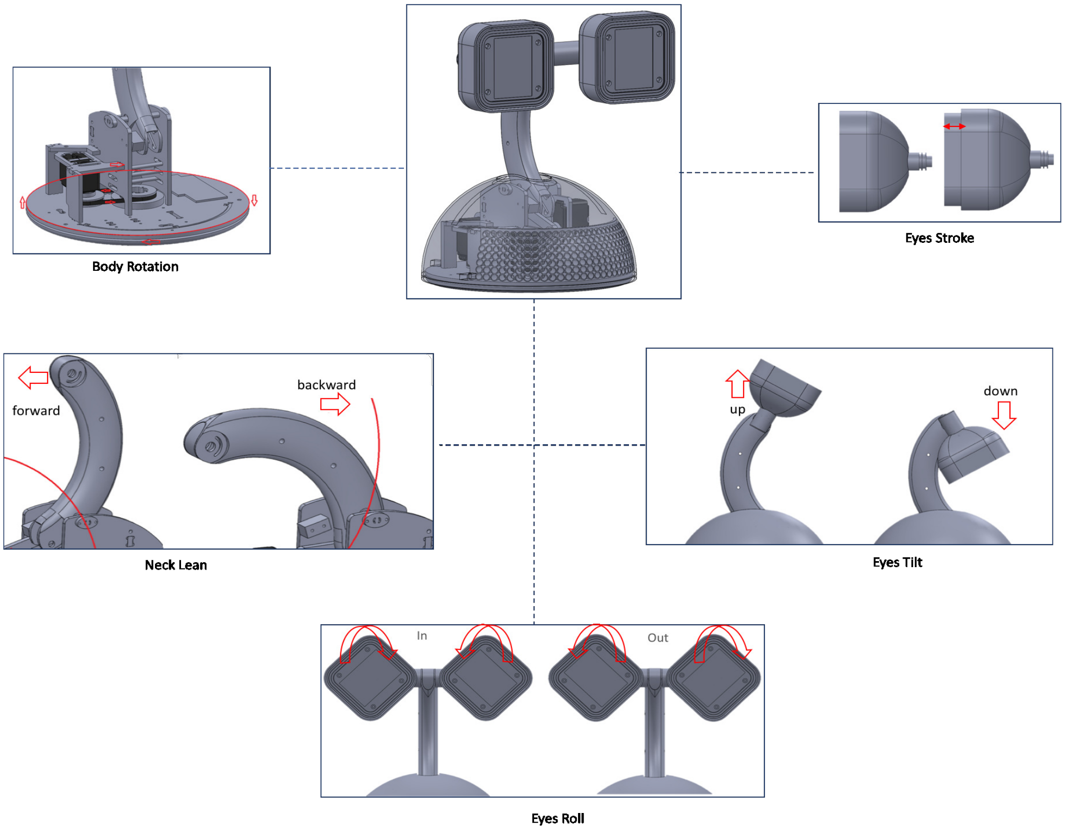

Fig. 3. Tabletop robot actuation

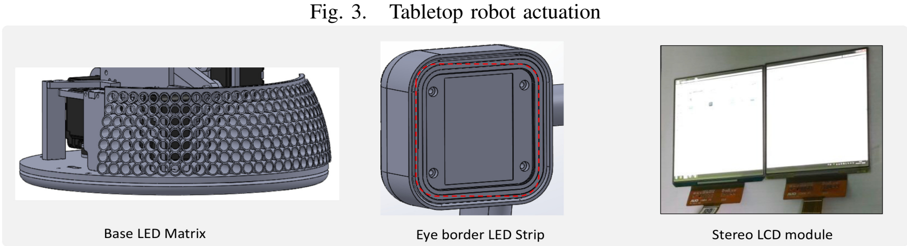

Fig. 4. Tabletop robot visuals

- Eyes Tilting Up and Down
  The eyes can tilt up and down with 60 degrees angle of displacement. Both eyes tilt simultaneously.
- Eyes Roll In and Out
  Both of the eyes will roll simultaneously inside and outside direction
- Eyes Stroke
  The third and final eye movement is the inner eyes' retract-detract actuation with a 15mm displacement. Both of the eyes can go inside or outside of the outer shell simultaneously.

B. Audio Visuals

- Eyes and Mouth LEDs
  Each of the eyes (inner part) is composed of a 3-inch TFT screen display as shown in Fig. 4. Moreover, the rectangular border of the inner eyes is composed of an addressable LED strip. Inside the body is an addressable LED matrix. The illumination from the LED matrix passes through the body from the inside out.
- Speaker
  The robot is also equipped with an internal stereo speaker for vocalization and sounds.

IV. Expressivity Through Animation Expertise

A. Designing Expressivity

In designing the form and articulation of a robot it is important to identify the primary feature that will be used for communicating expressiveness Although Haru's form is non-biological, its primary feature for communicating expressivity is its eyes. Studies have noted, that 43.4% of the attention we focus on someone is explicitly devoted to their eyes, with the mouth coming in second at only 12.6% [28]. How the eyes move, gaze, contract and dilate and make eye contact are factors that allow us to; perceive others as having minds, attribute mental states to others, coordinate social face-to-face interactions and assist in cooperative behaviour. Eyes can also act as hands as they direct the user to look, and even turn their body in the direction of the eye movement. Whilst Haru has speech affordance through TTS, an embodied communication approach was taken which placed an emphasis on multi-modal, non-verbal expressiveness produced through eye and body gestures and non-verbal vocalisations, with a particular emphasis on the eyes.

Haru has five Degrees of Freedom (DoFs), however a robots expressivity is not hampered by limited DoFs. Instead, it is dependent on how the DoFs are placed in relation to the primary feature used for communicating expressiveness. Three of Haru's DoFs relate directly to the eyes. The DoFs associated with Haru's eyes are: Eyes Tilting Up and Down, Eyes Roll In and Out, Eyes Stroke (retract/detract), with the other two DoFs - Body Rotation and Neck Leaning Forward and Backwards serving as gestural elements and also to position the eyes. Haru has additional 'digital' DoFs associated with the eyes as the 3- inch TFT screen that forms the inner eye allows for an up and down, side to side, arced and angled articulation and the ability to expand and contract the iris and pupil within the screen's dimensions. A further emphasis is placed on the eyes by the gestural possibilities of the rectangular border of LEDs that surround the inner eye.

B. Animating Expressivity through 12PA

Our aim with Haru's expressivity is to create a rich and diverse range of emotional affordances, social cues and gestural movements that bring novelty in longitudinal interactions, that allow Haru to engage in human-robot interaction in an adaptive manner and to cater towards the dispositions of specific ages, genders, cultural backgrounds and individualistic traits.

Motion capture data, a one-to-one direct translation of human gestural movement onto robots, is limited by the differences between a human and a robot's form and capabilities. Animators do not work with direct translation, they work with a process of simplification and abstraction to communicate emotional intent by making the most essential gestural movements more explicit in a way that allows people to easily understand the intended emotion. The articulation of this process is summarized in what are commonly known as the Twelve Principles of Animation (12PA)[29], These principles provide a basic framework for translating movement and expressivity into embodied mediums to produce 'the illusion of life' by adhering to the fundamental laws of physics, whilst dealing with more abstract issues such as design, emotional timing and character appeal.

The 12PA are defined under the headings: Squash and Stretch, Anticipation, Staging, Straight ahead action and pose to pose, Follow through and overlapping action, Slow in and slow out, Arcs, Secondary action, Timing, Exaggeration, Solid drawing and Appeal. Not all principles are applied to every action and the design of an intentional action, emotional or social cue may only require the application of a few of these principles at any given time. The main principles we have applied to Haru's expressivity are listed below with brief examples of their application :

- Squash and Stretch
  This principle gives a moving object a sense of weight and flexibility. By elongating or compressing an object during movement it emphasizes an object's speed, momentum, weight or mass. In its application to Haru's eye gestures, we have used it to emphasize the speed at which an eye darts from one eye position to the next when Haru is communicating the more exasperated feelings of panic or confusion.

- Anticipation
  This is a key principle in telegraphing intent. It does this by performing an action (usually in an opposite direction) before the main action. The more anticipation an object performs before the main action, the more expectation builds for the main action, and vice versa. For example, when animating the expression of sadness, Haru's eyes move briefly upwards before performing its main downward action, the neck moves slightly backwards before it moves fully-forward, whilst the eye stroke retracts inwards before pushing out to its full capacity by the end of the gestural movement. Another way in which we have applied anticipation to Haru's eye gestures is to make its eye blink prior to moving as blinking in order to indicate a change in movement or thought.

- Slow In and Slow Out
  Slow-in and slow-out describes the tendency for all movement to slowly accelerate and decelerate, this results in movement that is more natural in appearance. The absence of this principle can result in jarring, mechanistic movement. When applying slow in and slow out in directional eye or body gestures, the eyes or part of the body should slowly move in the appropriate direction, speed up, and then slow to a stop when it researches its destination. When designing Haru's expressivity for happiness and excitement, we applied less slow-in and slow-out to the movement of its eyes and body as the more sudden and rapid the movement that results communicates more intense bursts of emotion.

- Arcs
  Arcs highlight the organic quality of an object as most living creatures move their body parts in an arc. The lack of an arched trajectory results in mechanistic movement. The eyes should usually follow an arched trajectory when moving from one eye position to the next. We applied a more arched trajectory for to Haru's eyes and body movements for communicating Haru being bored and a less arched trajectory, which emphasizes speed and momentum, for communicating laughter.

- Timing
  This refers to the amount of time given towards a particular action and can affect how the personality or nature of a character is perceived. When applying the principle of timing to gestures, it is important to apply the appropriate amount of time between start and rest positions of a trajectory. The more time applied between the first and last position in a gesture, the smoother and more sustained the gesture will feel and vice versa. We applied less time between eye and body gestures for happy as it is an intense and bursting in emotion form of expressivity. More time was applied between Haru's eye and body movement points for communicating emotions such as sadness.

- Exaggeration
  The principle of exaggeration is key when working with robots as they do not possess the myriad of organic subtleties that humans possess and utilize when communicating. Exaggeration is a key principle applied to all the 12PA. The level of exaggeration determines the degree to which you apply each principle to a gesture. As a stand-alone principle, it refers to making the essence of an action clear. It should be important to note that exaggeration does not mean to make something more distorted or caricatured, but to make the motion more readable and convincing by making that action clear and present. More exaggerated movement gestures were applied to the more intense emotions such as excitement, extreme happiness, sadness etc.

To produce Haru's range of expressivity, we worked with a range of modalities that included body motion, sound, LEDs and eye gestures. To do this, we modeled, rigged and textured a 3D digital avatar of Haru that exactly matched its hardware specifications, animating the DoFs directly through the avatar. Eyes, LEDs and Mouths were animated as separate files as these would eventually be transferred individually. Added to this, acoustic emotional expressions were designed in two different acoustic 'languages' to allow for different approaches to Haru's personality. The first 'language' is percussive, with all sounds being made through percussive or musical means; the second is a non-verbal acoustic 'language' based on the human voice. The files containing the multimedia elements, such as GIFs for the eye and mouth LEDs, videos for the left and right eyes, audio for the sound, and the actuation elements, trajectory data for joints (base, neck, head, eyes roll, eyes stroke), were then exported from the avatar and packed into a routine file with an accompanying video reference. This package is then used to transfer the animation to the robot hardware in a manner that maintains the integrity of the inherent principles and techniques of animation that we have applied to the expressive movements.

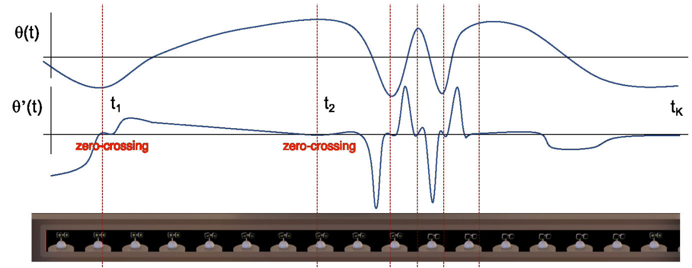

Fig. 5. Zero-crossing motion transformation.

V. Transferring Expressivity to Tabletop Robot

A. Animation-based method

We developed a tool to load the routine files generated by the animation software and import the different elements: GIF for the LEDs, videos for the eyes, audio files for the sound, and joint trajectories for base, neck, head, eyes roll, eyes stroke, respectively. The tool analyzes the data and perform necessary adaptation to comply with the dynamic constraints based on the general limits for the velocity and acceleration of the hardware. In particular, the tool checks if the animated trajectories comply with the actual dynamics. If not, then the tool transforms the motion so that the dynamic constraints of the robot are met and, at the same time, the synchronization of the motion with the multimedia elements (i.e., videos for eyes, eyes and mouth LEDs and sound for the speaker) are not lost. The goal is to transform the trajectories maintaining their shapes, meaning that the moments for the changes of direction of the joints are kept. This is done by analyzing the original motion of the joints $\theta_i(t), i \in \{$*body, neck, head, eye tilt, eye roll, eye stroke*$\}$ in the animation domain and transforming them through T to new motions $\eta_i(t)$ so that the timing of the zero-crossings of the velocity of the joints is maintained as shown in Fig. 5. We find transformation T in Eq. (1) such that:

$$\begin{gathered} \eta_i(t) = T[\theta_i(t)] \\ |\eta_i'(t)| < v_{i,max} \\ |\eta_i''(t)| < a_{i,max} \\ \forall t_k \mid \theta_i'(t_k) = 0 \implies \eta_i'(t_k) = 0 \end{gathered} \tag{1}$$

where $v_{i,max}$ and $a_{i,max}$ are the velocity and acceleration limits of joint i. This can be achieved by using the transformation T to scale the joint values. The initial joint trajectory $\theta_i(t)$ is discretized in time and the transformation is applied in the sectors where the constraints are not met. This way, the changes on the direction of the motion, as well as the duration of the motion as a whole, are kept synchronized with the rest of actuation of the robot. The transformed data is then exported to the robot hardware.

B. Manual composition method

The tool mentioned above also supports the generation of routines directly by hand and combine all actuators of the tabletop robot. The commands for the five joints can be set by demonstrating the trajectories using a joystick or the mouse, which are then recorded in the proper format. The tool also allows to determine the timed evolution of the addressable

TABLE I

RESULTS FOR ANIMATION-BASED AND MANUAL COMPOSITION FOR SIMPLE EXPRESSIONS

Simple Expressions	Animation-based	Manual composition
Happy	93.0%	66.0%
Sad	90.0%	60.0%
Angry	87.0%	50.0%
Fear	97.0%	37.0%
Shy	97.0%	33.0%

TABLE II

RESULTS FOR ANIMATION-BASED AND MANUAL COMPOSITION FOR COMPLEX EXPRESSIONS

Complex Expressions	Animation-based	Manual Composition
Laughter	100%	7.0%
Japanese Bow	100.0%	10.0%
Bored	90.0%	3.0%
Curious	87.0%	0.0%
Agreeing	100.0%	13.0%
Disagreeing	100.0%	10.0%

LEDs for the mouth and the eyes, and the source audios of the sounds for the speakers and for the videos for TFT of the eyes. The resultant routine can be also simulated. Timing and synchronization under this method is not straightforward.

VI. EVALUATION

A. Experimental Setup

We conducted two experimental conditions in evaluating the tabletop's expressivity. In the first condition (animation-based), the tabletop robot's expressions are generated using our proposed method described in Sec IV in which designers comfortably make use of the techniques and tools in the animation domain and then transfer these expressions to the hardware using the tool we developed as discussed in Sec V-A. In the second condition, expressions are manually composed directly using the same tool discussed in the Sec V-B. Two sets of expressions are prepared, the first set is comprised of simple expressions (i.e., happy, sad, angry and shy). The second set is comprised of a more complex expressions that are nuanced (i.e., laughter, japanese bow, bored, curious, agreeing and disagreeing). We gathered thirty participants (15 female and 15 male adult) to evaluate the two conditions discussed above. A very simple blind test was conducted in which we presented the participants with the animation-based and the manually generated expressions in pair, and asked them to "like" or "unlike" with the following instructions:

- to like only if an expression is well understood
- select only the best between the two conditions, if possible (double likes is allowed only if warranted)

The participants have no prior information as to which condition an expression being presented to them belongs to. We also randomize the order of the two conditions when presenting to the participants.

B. Results

The results of the experiment for both the simple and complex expressions are shown in tables I and II, respectively. These tables show that the animated-based method is preferred by the participants over manual composition for both simple and complex expressions. However, it can be observed that manual composition of expressions has the worst performance in the complex expressions in table II than simple expressions in table I. This is because nuanced expressions are more difficult to compose than simpler expressions. Lastly, the animation-based approach clearly beats the manual composition in table II, this means that the holistic treatment of modalities, synchronization, etc. that are the strong points of the animation-based method sets a clear boundary between the two methods. The results in tables I and II are not surprising since animation-based expertise has been utilized for generations in making animated movies which is more complex in nature.

VII. CONCLUSION

In this paper we have shown a method of applying animation expertise in developing the expressivity of the tabletop robot. Our approach enables designers to work in a domain in which they are comfortable with (animation domain), maximizing their full creative potential. Combined with engineering techniques, we are able to transfer expressive animation routines unto the robot hardware. In the future, we would like to perform more tests by increasing the currently limited vocabulary of expressions.

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