Design of a cost-efficient, double curvature display for robots

Anand Vazhapilli Sureshbabu*, Marco Maggiali*, Giorgio Metta* and Alberto Parmiggiani*

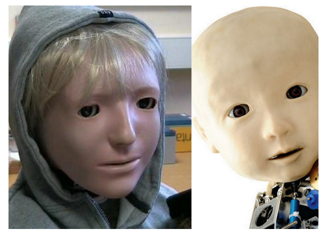
***Abstract*— A novel, low cost display which uses existing 3D printed optics technology and improves upon it by adding isolation and diffusion layers is presented. The display can transmit light source from a planar 2D surface through individual light pipes onto complex surfaces. This is achieved by a combination of total internal reflection of light in the light pipes which are embedded for minimum Fresnel losses, light isolation using structural limiters and by providing a light diffusion mask to augment contrasts. The resulting display is shown to exhibit higher contrasts, enhanced performance and minimal light loss due to scattering. An exhaustive evaluation was carried out and a user survey was done on the final result. The display is then mounted on the head of the new R1 humanoid robot.**

I. Introduction

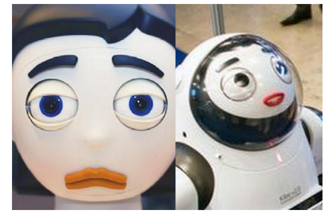
Humanoid robotics has made giant strides in the past decade but the design of a humanoid head that is widely accepted continues to be a challenge. Besides the evident technical challenges, relevant difficulties lie in the selection of the system to represent expressions. Features to materialize expressions that are too abstract could be misinterpreted, while features that imitate the human condition stand the danger of falling into the uncanny valley [1]. In this paper, a low cost head (Fig.1) for a new humanoid robot to be employed in human-centric environments is proposed to bridge the gap between the abstract and uncanny representation in humanoid faces.

Fig. 1: Proposed display: The cruved display presenting a neutral expression and mounted on the R1 humanoid robot (in picture)

The robotics community is split on the appearance of robot heads with many opting for anthropomorphic features [2] [3], while some others prefer abstract faces while yet others use screens that display iconic representations of human features. Different types of robot faces (Fig.2) include anthropomorphic faces, abstract faces or even simple display screens.

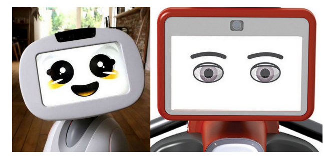


(a) Anthropomorphic - realistic



(b) Representative

(c) Abstract



(d) Display screens

Fig. 2: Types of faces in modern robots (from Top left) (a) Realistic anthropomorphic faces such as KASPAR [4], Affetto [5],(b) representative anthropomorphic faces, which do not replicate human features entirely such as FLOBI [6], KIBO [7], (c) Abstract faces which do not replicate or mimic any human features, such as Myon [8], HRP-2 [9] and (d) Display screens which are more straightforward such as Buddy [10], Baxter [11]

Robots whose functions mostly focus on navigation and SLAM tend to be endowed with abstract looking heads to mask the sensors underneath [7] [6]. Robots that are required to communicate with human users or operators often comprise a head based on a displaying device. Heads based on displaying devices can be subdivided into two main categories: plain display faces and projection-based display faces. Baxter [11] and Buddy [10] are two examples of the former category as they employ a simple screen to represent the robots' faces. Display screens, in addition to being a simplistic interface to displaying expressions, can also act as terminal to display relevant information if and when needed to aid the human user carry out a dialogue with the robot when other means of communication are limited. AIDA [12] and MASK-bot [13] instead rely on the use of a projector that projects images onto a screen or a virtual mask that has physical features that may or may not mimic anthropomorphism. This is useful for displaying more complex expressions as a it adds a layer of physicality on top of the existing virtual features of expressions. Projection-based displays are also comparatively simpler to construct than anthropomorphic faces and allow for quick customization when it comes to preferred gender or even identity. The application of this technology is however hampered by disadvantages such as visibility limitations in brightly lit

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scenarios, minimum projection distances, and the eventual need to employ additional mirroring. These altogether can in some cases cause negative feedback from users [13].

Another approach is the one being experimented by researches at Disney [14] that have recently demonstrated the feasibility of 3D printed optics to displace displaying surfaces from their original sources of illumination.

The paper is structured as follows; the main motivations behind building a display of this nature and discussions on the equivalent user requirements are described in Section II. Section III details the conceptual design based on requirements, followed by the discussion on the embodiment design in Section IV. An evaluation of the first prototype is carried out in Section V and the results and conclusions are briefed in the final section.

II. Motivation

The main motivation behind the design of the current display was to provide the R1 humanoid with an expressive face that is easy to understand. The end result of our efforts is represented in Fig.1. The use of human-mimetic faces, like in Affetto and KASPAR, was deemed unsuitable since they fell in the uncanny valley, and user surveys [15] have shown this problem became more apparent if the robot did not have human-like expressions, i.e., the expectations rose the closer the face resembled to that of a human [16]. The other challenging factor in bringing humanoid robots into homes was the cost. This gives the clear indication that neither representative nor realistic anthropomorphic heads are preferred. One of the options for simplicity sake was to place a display within the head of the robot capable of producing images and expressions simple enough to be discerned by children. However, the idea of a display screen gives off the impression of a tablet on a moving platform. Many people deem it to be mechanical and less-likeable in robots [16]. A useful guideline for selecting and designing a display that could satisfy such limitations is by Woods et al. [17] which can be summarized as follows:

1) robots should have cartoon like features, exaggerated facial features and be brightly colored for positive behaviors
2) robots should have realistic features, less clear facial features, and be dully colored to depict negative behaviors
3) the whole appearance of a robot should be considered at the outset of the design phase rather than focusing on specific aspects such as the face
4) it should not be designed to look completely human-like. A mixture of human-machine features is most desirable

These guidelines, although for child-robot interaction, was selected for the purposes of simplicity and clarity in representation. It was important for the display not to elicit high user expectation since realistic representation of the human face, when not done correctly, could lead to misinterpretation.

The overall look of the R1 humanoid was conceived by a design team that took these motivations into consideration. The head also had to be coherent with the overall look of the robot, hence the designers conceived of an abstract head for the R1 humanoid. Drawing from these preliminary guidelines, a list of higher level user requirements were drawn and are enumerated as follows:

- the display outputs a gamut of colors distinguished by the visible spectrum of the human eye
- the color reproduction is discernible and satisfactory; scores more than 80% value on the HSV scale for the core RGB colors
- the display module does not weigh more than 600g
- the display should not cost more than 10% of the total cost of the robot, i.e €1200
- the display should have enough resolution to display expressions efficiently; i.e, expressions displayed should be easily recognizable

To address all these issues a low cost display made from rapid prototyping technologies that enables the projection of images on complex surfaces was selected. This approach had the added advantage of avoiding the reduced intensity and illumination problems in daylight and ambient light that conventional displays suffer. The head and the display were to be curved to give the impression of a 3D surface, while maintaining visibility from different viewing angles. One further design requirement for the display was that it was required to be easily replaced and easy adaptation to allow seamless integration with the rest of the components of the head (e.g. 3D sensors, speakers, cameras etc.).

III. Conceptual design

Traditional methods for realizing displays where light projection is decoupled from the light source lie in the use of fiber optic cables due to their superior total internal reflection (TIR) properties. This idea was first extended to printed optics [14] in 2013. It was decided to further explore this concept to remove the shortcomings in the existing methods. Due to the low cost requirement and the complexity of projecting light on complex surfaces, the use of 3D printed objects was selected. Standard red-green-blue (RGB) light emitting diodes (LED) were chosen as the source of light for the display. The remaining part of the problem was then to transmit the light generated by the LED onto a curved surface; this was solved by creating custom light guides much like a fiber optic cable. Our solution to manufacture these light guides was to create a 3D printed optics module. The main drawback of this approach was that unless a lot of diffusion is applied after the light is conveyed on the projection surface a discrete and "pixelated" output would be seen . This aesthetic effect was nevertheless considered compliant with the overall look of the robot. Finally the requirement for design flexibility was solved by designing a modular display which was capable of conforming to shapes and confined to small spaces.

A. Printed optics module design

The basic concept of optic fibers is imitated in the new module design (Fig.3) by constructing the structure using 3D printing technology. The ”light guides” act as the transmission medium or the core.

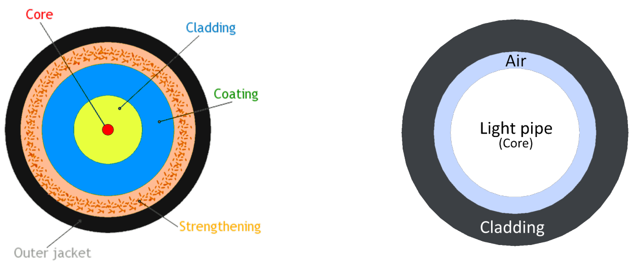


Fig. 3: Light transmission concept. Left: The traditional fiber optic light guide design. Right: The modified printed optics module design. Multiple layers are compounded to provide a simplified version of the internal reflection concept.

The cladding is then built surrounding the light pipe and it doubles up as the support structure that holds the light pipe in place. The cladding has a lower refractive index, that assists in reflecting back the light rays into the light pipe. When the light rays encounter the cladding at any angle above the ”critical” angle, the light achieves total internal reflection. The critical angle θ_c is given by Snell's law,

$$n_1 \sin \theta_i = n_2 \sin \theta_t \tag{1}$$

where n_1 and n_2 are the are refractive indices of the light pipe and cladding respectively and θ_i and θ_t are the angle of incident light from the LED and the refracted angle respectively. To find the critical angle, the value for θ_i is determined when $\theta_t = \pi/2$ and thus $\sin \theta_t = 1$. The resulting value of θ_i is equal to the critical angle θ_c. The resulting formula for the critical angle is given by:

$$\theta_c = arcsin\left(\frac{n_2}{n_1}\right) \tag{2}$$

The classical structure of fiber optic cables is restructured into just three layers of light pipe (core), support (cladding, coat and support) and a thin layer of air. The efficiency of TIR is controlled by varying the materials to achieve different refractive indices of the cladding and core material. The resulting transmitted light is then passed through a light diffuser for better contrast and uniformity in light distribution (as shown in Fig.4).

IV. Embodiment Design

The objective of this display is to provide a uniform illumination on multiple curvatures (concave and / or convex). The display as shown in Fig.5 is composed of a matrix of RGB light elements (pixels/element 1) that project light on the outer surface of the device. The light passes through the light pipe (element 2) which transfers the light on the outer surface of the display. The support structure (element 3) acts as a cladding and also isolates light passing through the light pipes. The surface is then covered by a transparent or semi-transparent diffusion plate, on which the image is displayed. The display needs to have adequate luminosity to be visible

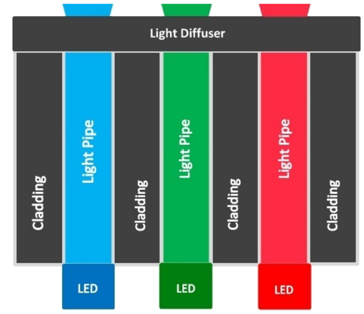


Fig. 4: Printed optics module structure. It can be observed that the LEDs are set in the “light pipes” structure which is then inserted into the cladding before being covered by the light diffuser or diffusion mask. The “light pipes” are in VeroClear, the cladding in PE and the light diffusion mask made of black Plexiglass.

in daylight. As a reference value the reader should consider that the average luminosity in daylight interior is around 500 lumens (lm).

A. Display Construction

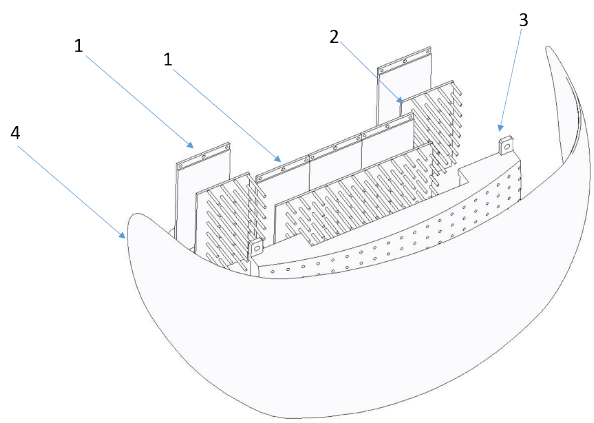


Fig. 5: Proposed display structure. The FML PCB Board (element 1) is placed on the light pipe structure (element 2) which is then inserted into the cladding (element 3). These are all then covered with a diffusion mask (element 4) which conforms to the shape of the cladding structure.

The light pipe (Fig.6) is the mechanical part made of a transparent material. This part can be obtained with different technological processes such as CNC machining, 3D printing or molding. The light source is an RGB LED 2x2mm size. The emitted light is carried by the light guide, that is made of a transparent material. For these purposes the VeroClear® material from Stratasys® was used. Parts were printed on a

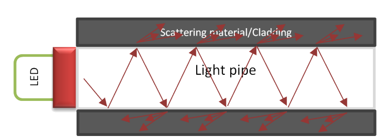


Fig. 6: Light pipe concept. This shows the total internal reflection concept as applied to our printed optics module.

Stratasys Connex 500 PolyJet® 3D printer; this machine has a print resolution of 0.1mm.

The terminal part of the guide has a surface roughness specially made to yield a homogeneous diffusion of the light over the end part of the guide. This part is important, because if made differently, would not allow the colors to diffuse effectively. As seen in Section II, to separate the light emitted by the various pixels and to guide the light pipe, another mechanical element, the cladding (element 3) is necessary. This was first tested with a 3D printed structure using VeroBlack. However, this structure was later replaced with a machined Polyethilene (hereafter referred to as PE) for increased robustness and accuracy. PE was specifically selected for its low density to reduce the total weight of the system. It should be noted that this element has holes in which the light pipes are inserted. The PE structure acts as the cladding and has a lower refractive index (around 1.36) compared to that of the light pipe (around 1.53). These guide holes in the cladding have a diameter that is 2mm greater than the light pipes themselves, so that there is a layer of air between the light pipe and the support material. This prevents the light from being absorbed by the support and acts as a second layer of cladding. In this way the cladding also allows the separation of the light that is emitted by adjacent guides. The outermost surface of the display, the light diffusion mask (element 4) will then be the single or double-curved surface which serves as a cover, displays the projected image, and hides the internal structure of the display. The black Plexiglas visor/mask that was used has a reflectance value of 20%.

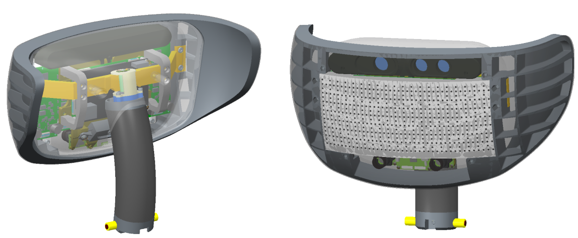


Fig. 7: Internal structure. Shows the arrangement of the sensors and the electronic boards in the head structure in conjunction with the display structure(shown in white)

B. Head Construction

As mentioned earlier the R1 head also houses a number of sensors and control boards as shown in Fig.7. The head comprises a frame mounted on a two DOF neck with a pitch and a yaw joint. The display is fixed onto a frame which also houses an ASUS Xtion Pro Live RGBD sensor. The head also houses two Leopard Imaging LI-OV580-STEREO stereo cameras, a microphone and an ABS-229-RC speaker which is situated just below the display module. Finally the head contains a low-cost and high-performance Single Board Computer (SBC) also dubbed "Z-turn board" built around the Xilinx Zynq-7010. This board is placed right behind the display module and controls most of the expression related activities of the robot: it controls the display, through the FML boards via the ZFC electronic board (details regariding these boards will be discussed more in detail in the following section), it processes stereo microphone data, and controls the speaker used to generate the voice of the robot.

C. Electronics

The electronics architecture of the proposed display is as shown in Fig.8. An FPGA-based board Z-turn board controls a number of FML cards (Element 1) connected in a chain. The FML boards are equipped with integrated circuits capable of handling 512 RGB LED present on the same board and arranged in a matrix (16 columns by 32 rows). We can connect up to 16 cards in an FML chain. In the current solution 5 FML boards are used, with a total of 80×32 pixels (2560 pixels). The light sources are RGB LED, 2×2mm in size. A more detailed breakdown of the display board is given in Tab.I.

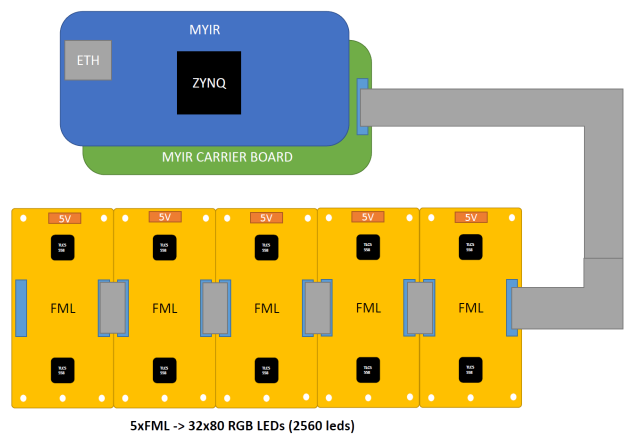


Fig. 8: Hardware architecture of the display

TABLE I: Properties of the modular display unit

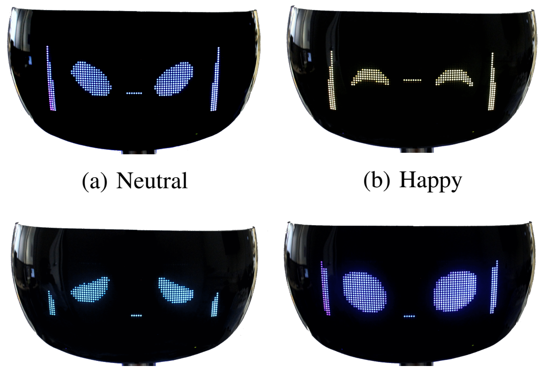
Properties	Value
No. Of FML modules	5
Number of pixels	2560
LED stacking per FML module	16 x 32
Refresh rate	50Hz
Communication protocol	USB
Image format	bitmap
Video format	mp4

V. Evaluation

The display was tested for its color rendering capabilities, but the most important metric was its capability of displaying the expressions of the R1 humanoid. All the other sensors and electronic boards fit well within the head with no unsightly deviations from the original proposed shapes. Details are discussed in the following sub-sections.

A. Expression perception

For the purposes of displaying expressions and notifications, the display performed well. The display satisfied the requirement of an effect different enough from that of a traditional LCD or OLED display and had enough resolution to show the images as not excessively disjointed. Some of the sample images of the expressions are as shown in Fig.9; these depict the basic human expressions modified for the robot.



(a) Neutral (b) Happy

(c) Sad (d) Surprised

Fig. 9: Sample expressions on the display

A multiple choice survey to study the basic intent behind each expression on the display was carried out. From the survey, 82 replies were received, of which 50 were male and 32 were female. The mean age of the participants was 33.8 years, ranging from 20 to 72. Concerning their experience with robots 37 reported none, 15 reported little, 12 reported some experience, and 18 participants indicated that their experience with robots was substantial. Most of the users who took the survey said they could correlate the face with a particular expression. The survey was done using four designs that indicated “neutrality, happiness, sadness and surprise”. Since the exact expression interpretation is influenced by each person’s individual perception, this was not deemed the major intent behind this test. The results of the survey showed that more than 86% agreed on the neutral expression, 60% agreed on happy, 95% on sad and 53% on surprised. But interestingly, the users correlated the displayed face to an expression more than 94% across all given inputs. This shows that the display can be used as an effective HRI interface to display expressions, which remains as the primary objective.

B. Weight analysis

The display was optimized by the use of low density PE to reduce weight. The other advantage of using machined PE is that it makes cleaning easier as the support material from rapid prototyping methods is absent and does not need to be removed. This was problematic since cleaning the support material after 3D printing was quite a challenge, especially in the cladding. The end weight of the display sub-assembly was in accordance with our initial user requirement of 600g.

C. Color output

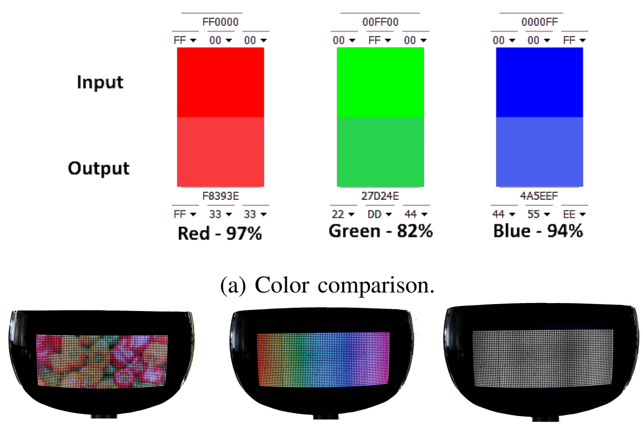
For this evaluation, all the pixels in the display module was set to either red (255,0,0), blue (0,0,255) or green (0,255,0) in the RGB color index.

The color comparison was done in ambient room lighting using a color grading software installed on a smartphone

TABLE II: Color reproduction analysis.

Color	Input values	Recorded values	Output [Input] H (deg)	S (%)	V (%)
Red	(255,0,0)	(248,57,62)	358 [0]	77	97
Green	(0,255,0)	(39,210,78)	134 [120]	81	82
Blue	(0,0,255)	(74, 94, 239)	234 [240]	69	94

(Ulefone Paris) with an OmniVision OV13850 camera with a 13MP sensor and a F2.2 lens. The recorded RGB output values are as shown in Fig.10a. A HSV grading of the output RGB values were also done. HSV stands for hue, saturation, and value, and is one of the most common cylindrical-coordinate representations of points in an RGB color model. The two representations rearrange the geometry of RGB in an attempt to be more intuitive and perceptually relevant than the cartesian (cube) representation. The HSV grading demonstrated (as shown in Tab.II) that all core colors performed well over 80% for color reproduction while there were problems in saturation values. This reduced color intensity could be due to the surrounding black cladding.



(a) Color comparison.

(b) Sample image (c) Color map (d) Gray map

Fig. 10: Performance maps. In (a) it is seen that the display has satisfactory reproduction values under the HSV norms while in (b) the displayed standard image was recognisable, while in (c) and (d) the classical color and gray maps are displayed

All the other display tests were also performed in ambient light. As can be seen in Fig.10, the color map clearly exhibits unique color distinction for the different core color gradients. The gray scale performed poorly as the distinction was less pronounced. Multichromatic images performed well for color reproduction but were affected by the resolution limitations of the display. The individual LED arrays were previously color calibrated. This study was solely to inspect the overall impact of the light pipes and the surrounding cladding on the reproducibility of colors on the finished screen.

D. Cost analysis

The cost of the display prototype is €1265 and the detailed cost breakdown is as shown in Tab.III. The cost estimation is for manufacturing a single display. For more than 100 pieces, the scaled down value for a manufactured and assembled unit can be reduced to €650, including assembling costs. As per the initial user requirement, this falls well within the projected cost. The overall cost of the head of the R1 including all the sensors and custom components for the increased quantity was estimated to be approximately €2100.

TABLE III: Cost breakdown of the display

Item	Pricing
Light pipes	€100
Cladding	€185
FML Modules	€950
Miscellaneous	€30
Total	€1,265

VI. CONCLUSION

The display was effective in evoking meaningful responses when it came to expressions according to user studies and the color reproduction were in keeping with the expected norms. The design stayed within the weight and cost requirements. Some observations and improvements are expanded below.

A. Observations

A pixelated display in place of a homogeneous display was successfully built as the focus was on improving clarity and never to provide a replacement for existing display technologies. The cladding acts as an insulator that avoids optical crosstalk and contributes to the pixel effect. The differential refractive indices between the transparent and opaque material facilitates total internal reflection of light which in turn aids in minimizing light leak. This gave clarity in illumination which is further aided by the curved diffusion mask.

Printing both the light pipe (the core) and the cladding together in a single structure with multi-material printing technology was also experimented with. The results were not satisfactory as the air gap proved to be important to reduce scattering losses, and the boundary between the cladding part and the light-guiding part was not sufficiently "sharp" because of the 3D printer resolution limitation. Providing a base structure at the bottom of the light pipes that allows the LED module to "set" inside the light pipes also reduced the scattering effect of the LED light.

B. Future work

The resolution of the LED matrix modules can be increased with less spacing than that of 2.5mm. At that point, the limitations related to the resolution depend on how thin the light-guides can be manufactured and how much light is lost in those guides. The external finish of the display mask can be blurred to augment the diffusion of the single pixels. Non-continuous displays by placing intermittent LED arrays are to be further explored.

Finally, further efforts should be devoted to conceiving an approach to the manufacturing of the display that would allow to obtain a module that does not require assembly or cleaning, while embedding "empty volumes" in the structure to further reduce weight.

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REFERENCES

[1] M. Mori, K. F. MacDorman, and N. Kageki, "The uncanny valley [from the field]," *IEEE Robotics & Automation Magazine*, vol. 19, no. 2, pp. 98–100, 2012.
[2] M. Blow, K. Dautenhahn, A. Appleby, C. L. Nehaniv, and D. Lee, "The art of designing robot faces: Dimensions for human-robot interaction," in *Proceedings of the 1st ACM SIGCHI/SIGART conference on Human-robot interaction*, pp. 331–332, ACM, 2006.
[3] K. Kaneko, F. Kanehiro, M. Morisawa, K. Miura, S. Nakaoka, and S. Kajita, "Cybernetic human hrp-4c," in *Humanoid Robots, 2009. Humanoids 2009. 9th IEEE-RAS International Conference on*, pp. 7–14, IEEE, 2009.
[4] K. Dautenhahn, C. L. Nehaniv, M. L. Walters, B. Robins, H. Kose-Bagci, N. A. Mirza, and M. Blow, "Kaspar–a minimally expressive humanoid robot for human–robot interaction research," *Applied Bionics and Biomechanics*, vol. 6, no. 3-4, pp. 369–397, 2009.
[5] H. Ishihara, Y. Yoshikawa, and M. Asada, "Realistic child robot affetto for understanding the caregiver-child attachment relationship that guides the child development," in *Development and Learning (ICDL), 2011 IEEE International Conference on*, vol. 2, pp. 1–5, IEEE, 2011.
[6] I. Lütkebohle, F. Hegel, S. Schulz, M. Hackel, B. Wrede, S. Wachsmuth, and G. Sagerer, "The bielefeld anthropomorphic robot head" flobi".," in *ICRA*, vol. 3, pp. 3384–3391, 2010.
[7] "Kibo.".
[8] M. Hild, T. Siedel, C. Benckendorff, C. Thiele, and M. Spranger, *Myon, a New Humanoid*. Springer, 2012.
[9] K. Kaneko, F. Kanehiro, S. Kajita, H. Hirukawa, T. Kawasaki, M. Hirata, K. Akachi, and T. Isozumi, "Humanoid robot hrp-2," in *Robotics and Automation, 2004. Proceedings. ICRA '04. 2004 IEEE International Conference on*, vol. 2, pp. 1083–1090 Vol.2, April 2004.
[10] B. Robotics, "Buddy," vol. 1, p. 15, 2015.
[11] R. Robotics, "Baxter," *Retrieved Jan*, vol. 10, p. 2014, 2013.
[12] K. Williams and C. Breazeal, "Reducing driver task load and promoting sociability through an affective intelligent driving agent (aida)," in *IFIP Conference on Human-Computer Interaction*, pp. 619–626, Springer, 2013.
[13] T. Kuratate, Y. Matsusaka, B. Pierce, and G. Cheng, "mask-bot: A life-size robot head using talking head animation for human-robot communication," in *Humanoid Robots (Humanoids), 2011 11th IEEE-RAS International Conference on*, pp. 99–104, IEEE, 2011.
[14] K. Willis, E. Brockmeyer, S. Hudson, and I. Poupyrev, "Printed optics: 3d printing of embedded optical elements for interactive devices," in *Proceedings of the 25th annual ACM symposium on User interface software and technology*, pp. 589–598, ACM, 2012.
[15] D. Hanson, A. Olney, S. Prilliman, E. Mathews, M. Zielke, D. Hammons, R. Fernandez, and H. Stephanou, "Upending the uncanny valley," in *Proceedings of the national conference on artificial intelligence*, vol. 20, p. 1728, Menlo Park, CA; Cambridge, MA; London; AAAI Press; MIT Press; 1999, 2005.
[16] A. M. Rosenthal-von der Pütten and N. C. Krämer, "How design characteristics of robots determine evaluation and uncanny valley related responses," *Computers in Human Behavior*, vol. 36, pp. 422–439, 2014.
[17] S. Woods, K. Dautenhahn, and J. Schulz, "The design space of robots: Investigating children's views," in *Robot and Human Interactive Communication, 2004. ROMAN 2004. 13th IEEE International Workshop on*, pp. 47–52, IEEE, 2004.