

MECHANICAL DESIGN OF THE HUGGABLE ROBOT PROBO

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This paper reports on the mechanical design of the huggable robot Probo. Its intentions include human–robot interaction (HRI), both physical and cognitive, with a special focus on children. Since most of the communication passes through nonverbal cues and since people rely on face-to-face communication, the focus of Probo’s communicative skills lies initially on facial expressions. The robot has 20 high-precision motors in its head and body. They are used to actuate the ears, eyebrows, eyelids, eyes, trunk, mouth, and neck. To build safety aspects intrinsically in the robot’s hardware, all the motors are linked with flexible components. In case of a collision, the robot will be elastic and safety will

be ensured. The mechanics of Probo are covered by protecting plastic shells, foam, and soft fur. This gives Probo's animal-like look and makes the robot huggable.

Keywords: Robotics; design; interaction.

1. Introduction

The upcoming generation of robots will collaborate with humans in many aspects of the daily life: from domestic tasks to elderly, health, and child care. Communication is hereby essential. More than 60% of human communication is nonverbal, mostly by facial expressions.¹ Therefore, it is very important to develop robots that are able to reproduce and interpret these expressions. The ability of these robots to interact and communicate with people in a natural, intuitive, and social way makes that humans get familiar and related to them. Hence, these robots are equipped with issues such as personality, facial expressions, gestures, and social intelligence. This paper describes the design of the huggable social robot Probo. Probo will be used as research platform for Human-robot interaction (HRI) studies with a special focus on children. The main design features for Probo are emotional face-to-face communication and safe interaction. In Sec. 2, a comparison is made between Probo and major other social robots. The two most important novelties of Probo are derived: first of all, Probo is covered by a soft fur and the robot is actuated by compliant actuators for its huggable and safe characteristics. In Sec. 3, the design criteria are listed, followed by the actuators used and a presentation of the different anthropomorphic expressive and motion systems. At the end of this paper, the conclusions are drawn.

2. Comparison

Probo is compared with the major other social robots in Tables 1 and 2. In these tables, the robots' main features related to Probo are presented. The column with the header *Type* describes roughly the form and size of the presented robots. The column with the header *DOFs* (degree of freedoms) indicate the actual number of DOFs, but can also be used to indicate the level of complexity of the robot. Since each DOF refers to the ability to translate or rotate assemblies or parts relative to each other, it is clear that a robot with a large number of DOFs equals a very articulated system that quite often consists of a large number of different complex subsystems that allow these movements. Therefore, one can assume that the level of complexity increases with the number of DOFs. Whatever possibilities the presented robots have to display some facial expressions are presented in the fourth column with header *Expressive face*. For instance, *Mechanical* indicates the possibility to move facial parts, *LED* or *OLED* indicates that the expressions are generated by use of, or projection of LEDs. The level of expressiveness is indicated by a range varying from *limited* to *extreme*. The fifth column with header *Skin* indicates whether or not the presented robots' faces are covered with some sort of flexible material. Solid

Table 1. Comparison Probo with state of the art robots. Part I.

Name Robot	Type	DOFs	Expressive Face	Skin	Compliant	Gestures/ Manipulation	Mobility
Probo	Animal-like, imaginary creature	20	Yes (very) mechanical	Yes Fur	Yes SEE	No/No	No
Kismet ²	Anthropomorphic head	21 (21)	Yes (very) mechanical	No	No	No/No	No
Leonardo ³	Animal-like, imaginary creature	69 (32)	Yes (extreme) mechanical	Yes Fur	Yes Voice Coil	Yes/Yes	No
Nexi, MDS ^{3,4}	Humanoid, child-size	35 (19)	Yes (very) mechanical	No	No	Yes/Yes	Yes Wheeled
WE-4RII ⁵	Humanoid, human-size	59 (28)	Yes (very) mechanical	No	No	Yes/Yes	No
Golden Horn ⁶	Expressive, head-torso	12 (10)	Yes (very) mechanical, LED	No	No	Yes/No	No
Doldori ⁷	Expressive head	12 (12)	Yes (very) mechanical, LED	No	No	No/No	No
EDDIE ⁸	Expressive head	23 (23)	Yes (very) mechanical	No	No	No/No	No
iCat ⁹	Animal-like, cat	13 (13)	Yes (very) mechanical	No	No	No/No	No
The Huggable ¹⁰	Animal-like, teddy bear	8	Yes (limited) mechanical	Yes Fur	Yes Voice Coil	Yes/No	No
TOFU ^{3,11}	Animal-, cartoon-like	N/A	Yes (limited) OLED	Yes Fur	Yes SEE	No/No	No
iCub ¹²	Humanoid, child-like	53	Yes (limited) LED	No	No	Yes/Yes	Yes Crawling

Table 1. (*Continued*)

Name Robot	Type	DOFs	Expressive Face	Skin	Compliant	Gestures/ Manipulation	Mobility
KOBIAN ¹³	Humanoid, human-size	48	Yes (moderate) symmetric, mechanical	No	No	Yes/Yes	Yes Walking
Albert HUBO ¹⁴	Humanoid, Android	66	Yes (very) mechanical	Yes Frubber	No	Yes/Yes	Yes Walking
HRP-C4 ¹⁵	Humanoid, Android	42	Yes (moderate) mechanical	Yes Silicone	No	Yes/Yes	Yes Walking
Repliee Q2 ¹⁶	Human-like, Android	42	Yes (extreme) mechanical	Yes Silicone	Yes Pneumatic	Yes/No	No
Geminoid ¹⁷	Human-like, Android	50	Yes (extreme) mechanical	Yes Silicone	Yes Pneumatic	Yes/No	No
SAYA ¹⁸	Human-like, Android	27	Yes (very) mechanical	Yes Urethane	Yes Pneumatic	No/No	No
AIBO ¹⁹	Animal-like, dog	N/A	Yes (limited) LED	No	No	Yes/No	Yes Stepping
NeCoRo ²⁰	Animal-like, cat	15	Yes (limited) mechanical	Yes Fur	No	Yes/No	No
Pleo	Animal-like, dinosaur	14	Yes (limited) mechanical	Yes Silicone	No	Yes/No	Yes Stepping
Ifbot ²¹	Mobile, expressive	14	Yes (very) LED, mechanical	No	No	Yes/No	Yes Wheeled
QRIO ²²	Humanoid, medium-size	38	No	No	No	Yes/No	Yes Running
Nao ²³	Humanoid, medium-size	25 or 21	Yes (minimal) LED	No	No	Yes/Yes	Yes Walking
EMIEW 2 ²⁴	Humanoid, medium-size	N/A	No	No	No	Yes/N/A	Yes Wheeled, Walking
Robovie-IV ²⁵	Service, medium-size	N/A	No	Yes Textile	No	Yes/No	Yes Wheeled
Wakamaru ²⁶	Service, medium-size	N/A	No	No	No	Yes/No	Yes Wheeled

Table 2. Comparison Probo with state of the art robots. Part II.

Name Robot	Type	DOFs	Expressive Face	Skin	Compliant	Gestures/ Manipulation	Mobility
Probo	Animal-like, imaginary creature	20	Yes (very) mechanical	Yes Fur	Yes SEA	No/No	No
eMuu ²⁷	Expressive, one-eyed head	2	Yes (moderate) mechanical	No	No	No/No	No
ROMAN ²⁸	Human-like head	21	Yes (very) mechanical	Yes Silicone	No	No/No	No
FEELIX ²⁹	Humanoid, LEGO	4	Yes (minimal) mechanical	No	No	No/No	No
CASIMIRO ³⁰	Expressive head	11	Yes (moderate) mechanical	No	No	No/No	No
Robota ³¹	Humanoid, small-size, doll-like	23	Yes (moderate) mechanical	No	No	Yes/No	No
Paro ³²	Animal-like, baby seal	9	Yes (limited) mechanical	Yes Fur	No	Yes/No	No
Keepon ³³	Expressive	4	No	Yes Rubber	Yes SEE	Yes/No	No
Kaspar ³⁴	Humanoid, child-size	14	Yes (minimal) mechanical	No	No	Yes/No	No
Infanoid ³⁵	Humanoid, child-size	29	Yes (moderate) mechanical	No	No	Yes/Yes	No
ARMAR III ³⁶	Humanoid, human-size	43	No	No	No	Yes/Yes	Yes Wheeled

plastic covers are excluded. The column with header *Compliant* refers to the use of compliant actuators in the robots. This means that a soft or compliant behavior is introduced intrinsically in the system by the actuation mechanism. In Sec. 3.3, related issues are described into more detail. The second last column with header *Gestures/Manipulation* shows whether or not the presented robots are able to show gestures by the use of body parts and/or arms. Furthermore, it indicates whether or not the robots have manipulation skills by the use of hands. The last column indicates the mobility of the presented robots. In this context: walking refers to bipedal walking; running is bipedal motion and includes a moment where both legs are of the ground; crawling refers to motions on arms and legs; stepping refers to quadruped motion; and wheeled refers to *Segway*-type and/or multiple-wheel-based motions.

Regarded to Probo's main goals, enabling HRI by face-to-face communication, it is clear that the expressive head is a key feature of Probo. In the first nine rows of Table 1, Probo is compared with robots with very expressive capabilities by the use of nonhuman-like heads. All human-like heads were excluded, because of Probo's esthetics does not strive for human-likeness. Between brackets is mentioned the number of DOFs of only the head. Therefore, all DOFs regarded to the gesture, manipulation, and mobility aspects of the presented robots are subtracted from the total number of respective DOFs. One can notice that, except *Leonardo* and Probo, none of these robot heads is covered with some sort of skin or fur. Furthermore, none of the presented robots, except *Leonardo* and Probo, uses compliant actuators. May these two properties, the use of soft and flexible materials in combination with compliant actuation, just be the most important key features to create a huggable and intrinsic safe design. Then, it becomes clear that in this context Probo is not comparable with any other existing robot at the moment, except the extreme advanced and complex robot *Leonardo*.

The remaining DOFs for facial expressions and head motions of the selected robots are divided among different expressive systems. Table 3 presents the actuated systems of the selected robot heads. Compared to the other robot heads, Probo's

Table 3. Comparison DOFs Probo with DOFs other expressive heads.

	Probo	Kismet ²	Nexi, MDS ^{3,4}	WE-4RII ⁵	Golden horn ⁶	Doldori ⁷	EDDIE ⁸	iCat ⁹
	DOFs							
Total	20	21	19	28	10	12	23	13
Eyes	3	3	3	3	4		3	3
Eyelids	2	2	7	6	4	4	4	2
Eyebrows	4	4	4	8		2	4	2
Lips	2	4		4		4	4	4
Yaw	1	1	1	1			1	
Trunk	3			2				
Ears	2	4					6	
Crown							1	
Neck	3	3	4	4	2	2		2

head offers a complete set of expressive facial parts, with a relative small set of DOFs. The DOFs in Probo's head are based on the *action units* (AUs) defined by the *Facial Action Coding System* (FACS) originally developed by *Paul Ekman* and *Wallace V. Friesen*.³⁷ They determined how the contraction of each facial muscle, or the combinations of facial muscles, changes the appearance of the face. They defined the measurement units as AUs, instead of muscles, for two reasons. First, for a few appearances, more than one muscle were combined into a single AU because the changes in appearance they produced could not be distinguished. Second, the appearance changes produced by one muscle were sometimes separated into two or more AUs to represent relatively independent actions of different parts of the muscle. The AUs and FACS are widely used for measuring and describing facial behaviors, even in robotics.

The desired combinations of AUs for emotional expressions, according to *Ekman* and *Friesen*,³⁷ are presented in Table 4. This table poses that there are different possibilities of combining AUs to express a certain emotion. The combination(s) Probo use(s) to express an emotion, based on its limited set of DOFs and AUs, is checked by a "v." Furthermore, the main actuated parts to express the emotion are presented. As one can see, it must be possible to express all the proposed emotions. This is evaluated by recognition experiments described in earlier work.³⁸

Table 4. Desired combinations of AU for emotional expressions according to *Ekman* and *Friesen*.³⁷ Probo's possible combinations.

Emotion	AU (Appendix)		Probo
Happy	12	v	Lips
	6 + 12		
	7 + 12		
Sadness, Distress	15	v	Lips
	6 + 15		
	11 + 17	v	Lips
Fear	11 + 15	v	Lips
	1 + 2 + 4	v	Eyelids, Eyebrows
	20		
Anger, Rage	4 + 5	v	Eyelids, Eyebrows
	4 + 7		
	4 + 5 + 7		
	17 + 24		
Surprise	23		
	1 + 2 + 5	v	Eyelids, Eyebrows
	1 + 2 + 26	v	Eyebrows, Yaw
Disgust	1 + 2 + 5 + 26	v	Eyelids, Eyebrows, Yaw
	9	v	Trunk
	10		

3. Design Probo

3.1. Design criteria

Worldwide there are only a few robots capable of expressing emotions, and since this research field has gained much interest in the research community, the development of an own robot platform is necessary. The main goal of the huggable Probo is to be a multidisciplinary research platform to study cognitive HRI including aspects of artificial intelligence, vision, speech, touch, and emotions with a special focus on children. The main design criteria were:

- *Identity, name, and history*: To intensify Probo's appearance, Probo has been given a name and there is thought of a story about its existence. For more information about this is referred to Ref. 39.
- *Social interaction*: For social communication, the robot needs to give the impression that it has an emotional state. The incorporation of emotions includes emotional systems in terms of hardware and in terms of software. Probo's facial expressions and emotions must be mechanically rendered. Therefore, the head of Probo must be equipped with a certain number of DOFs. The motors have to generate smooth and natural motions that must operate at human interaction rates.
- *Uncanny valley*: In order to avoid the uncanny valley,⁴⁰ the appearance of Probo is based on a imaginary or nonexistent animal. With this approach, there are no exact similarities with well-known creatures and consequently there are barely expectations of what Probo should do or not do. This would be the case if one presents for instance, a dog or a cat robot. Then children may expect the robot dog to bark and the cat robot to meow. If the robots do not succeed to their expectations they can become uncanny.
- *Green color*: Probo's color is chosen *lite green*. In Ref. 41, the relationship between color and emotion was studied, whereas the color green attained the highest number of positive responses. The majority of emotional responses for the green color indicated the feelings of relaxation and calmness, followed by happiness, comfort, peace, hope, and excitement. Green is also synonymous with nature and is now used widely as a term referring to environmentally friendly products or practices. Furthermore, green is a symbol of health.
- *Huggable*: Regarding Probo's physical embodiment and its emotional communicative skills communication between Probo and a child can already be set up. However, Probo aims physical interaction as well. This desire implements other requirements that need to be fulfilled; therefore, the robot must have a soft touch and huggable appearance.
- *Safety*: Since physical HRI is targeted, one of the most important design criteria is safety. This is achieved by using lightweight structures, compliant actuators, and a soft fur.
- *User-friendly*: Besides Probo's child friendly design, in terms of its soft and huggable appearance and emotional representation, Probo needs user-friendliness

in a different way. The Probo platform must be controlled, operated, and maintained by a whole group of various people with different backgrounds, for instance, medical staff, such as physicians and nurses, or psychologists, sociologists, pediatricians, and therapists. To succeed in this goal, abstraction and modularity play an important role in the design of hardware and software components. This means that abstraction layers on top of the control of the motors and analysis of the sensors are needed.

- *Autonomy*: In Refs. 42 and 43, it is stated that autonomy is one of the defining factors for HRI. There is a continuum for robot control ranging from teleoperation to full autonomy; the level of human–robot interaction measured by the amount of intervention required varies along this spectrum. For Probo, a shared control between the operator and the reactive systems of the robot is targeted. The first autonomous systems should focus on primary and life-like functions such as gazing and basic emotional expressions. Gradually autonomy can increase together with the control interfaces of the operator, giving the operator higher levels of abstraction.
- *Modular*: The robot must be modular both in hardware as software. Modular design is an attempt to combine the advantages of standardization with those of customization. In the design of the robot’s hardware, the use of different building blocks or components is a must.

3.2. Schematic overview hardware

A schematic overview of the actual Probo prototype hardware architecture is presented in Fig. 1. This scheme presents the internal hardware of Probo with exclusion of the perceptual sensory. In the scheme, it can be seen that Probo consists of different functional systems such as the eye-system, the eyebrow-system, the ear-system, the mouth-system, the trunk-system, and the neck-system. These are presented by the light-gray columns. All these systems have the same function, namely the creation of motions and expressions. In order to do so, these systems are built out of different structural mechanical assemblies, including actuated parts, actuators, motor controllers, wires, and sensors. These subsystems can be grouped in different layers. Each layer describes the main function of the grouped subsystems. There are five layers described as:

- (1) Motion and expression layer,
- (2) Actuation layer,
- (3) Low-level drive layer,
- (4) Supply layer, and
- (5) High level drive layer.

3.3. Actuators

The prototype of Probo has a fully actuated head with a total of 20 DOFs. By using compliant actuators with soft and flexible materials, a huggable and soft behavior

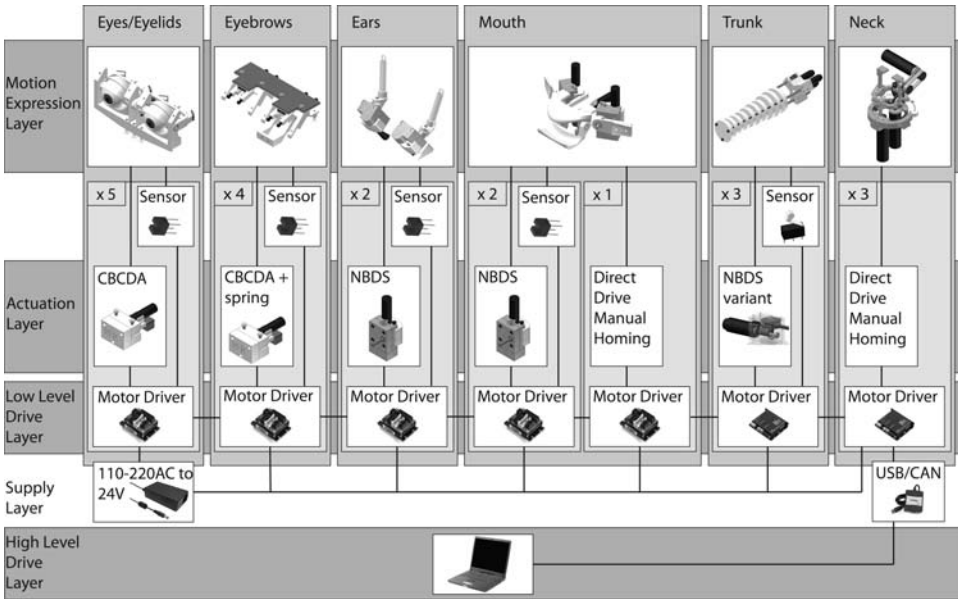


Fig. 1. Schematic overview hardware structure of the Probo prototype.

of Probo is achieved. Traditional actuators as electrical drives with gearboxes are unsuitable to use in Probo because they are stiff, giving an unsafe behavior and an unnatural hard touch. Two special actuation systems are introduced in the actuation layer to comply with the hardware design specifications:

- *Non-back drivable servo (NBDS)*⁴⁴ is a custom made servo motor system that mainly consists of a DC motor, a non-back drivable gear train, and a control unit (see Fig. 2). They are always combined with flexible components and materials such as springs, silicon, and foam.
- *Compliant Bowden cable-driven actuator (CBCDA)*⁴⁴ is a custom-made passive compliant servo motor system that transmits motion over a relative long distance compared to its own size, using a Bowden cable mechanism. The use of the CBCDAs creates the opportunity to group and to isolate the different actuators and to place them anywhere in the robot (see Fig. 3).

In both actuators, the flexible element plays an essential role since it decouples the inertia of the colliding link with the rest of the robot, reducing the potential damage during impact.⁴⁵ In a joint actuated by a CBCDA, the compliance is inherently present by the use of elastic Bowden cables. Joints actuated by a NBDS will be followed by a series of elastic elements such as springs and foam to become compliant.

An elaborate reflection on the actuators is presented in earlier work by the same authors.⁴⁴ In that work, Probo's actuators are compared with other innovative

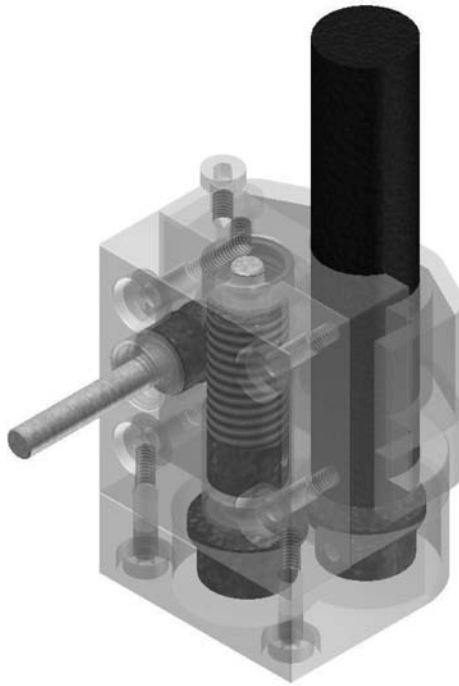


Fig. 2. Transparent view of the CAD-model to explain the working principle of the NBDS. The motor drives the idler gear via the pinion gear and is followed by a worm-wormwheel reduction. The axis that holds the wormwheel is the outgoing shaft.

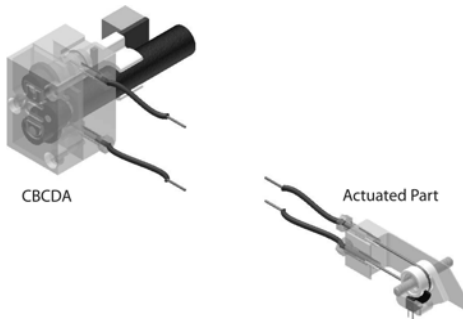


Fig. 3. A typical setup of a joint actuated by a CBCDA. The transmission of motion occurs by the inner cable in an outer cable housing over a long distance (the middle part of the cable is trimmed in the figure).

compliant actuators. The working principle of the CBCDA is described in detail, and experiments to determine the compliance of the CBCDA are presented. Furthermore a friction model is determined and evaluated experimentally. For both the NBDS and CBCDA, bandwidth tests are presented as well. In the online version of the referred work, one can see demonstrations of the actuators.

3.4. Anthropomorphic expressive and motion systems

In this section, the expressive and motion systems will be described into detail. These systems actually determine the expressive behavior and the motion of Probo's head. This head is supported by the neck-system. In Figs. 4 and 5, respectively, a CAD-model of the entire setup and a section view of the real Probo prototype are presented.

3.4.1. Eyes and eyelids (5DOF)

There are different reasons to equip Probo with actuated eyes. First of all, the eyes are used to show facial expressions. Furthermore, the eyes can be used to enable eye-gaze-based interaction (Figs. 6 and 7). When two people cross their gaze, they have eye contact. This enables communication. The same phenomenon between Probo and a child will be used to encourage HRI.⁴⁶ People use eye-gaze to determine what interests each other. By focusing Probo's gaze to a visual target, the interactors can use Probo's gaze as an indicator of its intentions. This greatly facilitates the interpretation and readability of Probo's behavior, since the robot reacts specifically to what it is looking at Ref. 47. Since humans always tilt both eyes together, Probo's eyes have three DOFs. Each eye can pan separately and both eyes tilt together. By panning the eyes individually, the eyes can focus on objects at different distances. The upper eyelids are actuated separately, allowing the robot to wink, blink, and express emotions.



Fig. 4. CAD of Probo.



Fig. 5. A section view of the real Probo prototype.

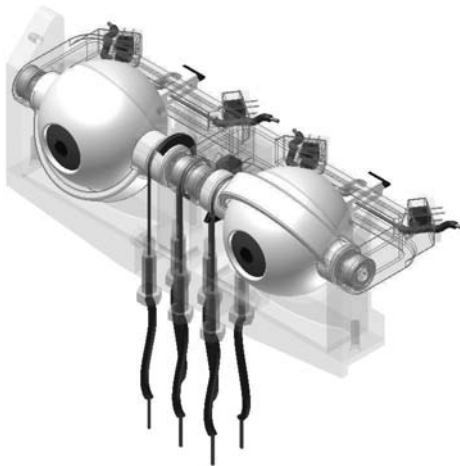


Fig. 6. Front view. Remark the eyelids and the rod to tilt the eyes.

What differentiates Probo's eye-system from common other robotic eyes are its esthetics and its way how the DOFs are actuated. By supporting the eye-spheres in an orbit, there are barely mechanical parts visible, what is quite often the case in other robotic heads. Often the eye-spheres are supported by concentric rings. Consequently, when the eyes are panning or tilting, these rings can become visible



Fig. 7. The backside of the system. The rods to pan the eyes are highlighted in blue.

for the interactor. This leads to an uncanny feeling. A possible solution to hide the rings is by placing an analog mechanism (e.g., a cardan joint) inside the eye-sphere. Then the possibility to install a camera inside the eye-sphere is lost, due to the lack of internal place. By placing the eye in an orbit, one can let the eyes bulge out of the system. Esthetics materials such as fur or skin can be fitted very properly to the eye-sphere, without influencing the working principle. That way the uncanny feeling, caused by visual mechanical parts, is avoided when looking at the eyes. Compliance is introduced in the eye-system by the use of the CBCDAs. The compliance of the actuated parts is sensible when they are removed from their equilibrium position. Small deviations are possible. By adjusting the barrel adjusters manually on the side of the actuators, and the side of the presented eye-system, the compliance can be pre-set before operation. The CBCDA allows to position the motors for the eye-system in the body to reduce the weight of the head.

3.4.2. Eyebrows (4DOF)

According to the early presented FACS, the eyebrows play an import role in facial behaviors. Referring to Table 4, one can see that eyebrows are required to express emotions such as fear, anger, and disgust.

Figure 8 presents the system. Each eyebrow has two DOFs as depicted in Fig. 9. The eyebrow (colored brown) itself is constrained by two ball joints. Each ball joint that constrains an end of an eyebrow, is fixed to a rod. By pulling cables, it will rotate around the centerline and raise the eyebrow's ends (Fig. 9), constrained by the ball joints. The antagonistic work to lower the eyebrow is now delivered by the helical torsion springs. Each cable, which rotates a rod, and consequently raises an eyebrow end, is actuated by a CBCDA. In comparison with the eye-system, the CBCDAs used in the eyebrow-system will only be used to actuate one cable

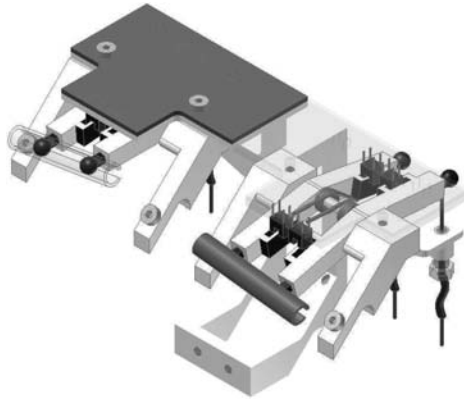


Fig. 8. Transparent front view of CAD model.



Fig. 9. Some examples of different possible eyebrow positions.

instead of two, since the actuated cable's antagonist is now replaced by the helical torsion spring.

3.4.3. Ears (2DOF)

Probo's ears are used to intensify its emotional facial expressions. According to the FACS, there are no human counterparts, but they move somewhat like that of an

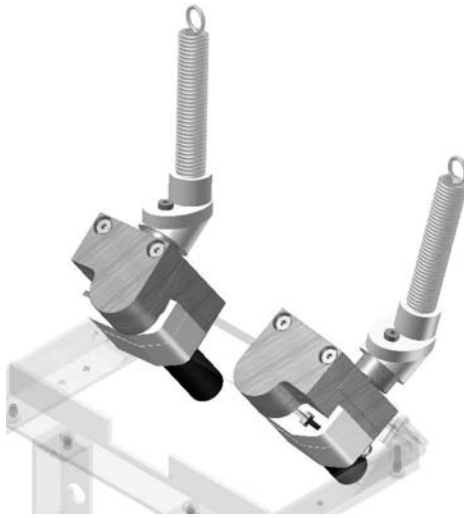


Fig. 10. Probo's flexible ears actuated by NBDSs.

animal. Probo has two ears. Each ear has one single DOF. Figure 10 shows the basic ideas of the ear-system. Two NBDSs are used to actuate the ears. The ear itself is a helical spring. This spring is fixated with one end to the output shaft of its actuating NBDS, while the other end can be moved freely around its centerline. A flexible foam core in the shape of the ear is placed over the spring. When the NBDS's output shaft is turning, it will rotate the constrained foam ear. The use of the flexible materials in combination with the helical spring, which can bend in all directions, will ensure the compliant feeling during interaction.

In comparison with Kismet's ears,² Probo's ears have less DOFs. Kismet's ears have two DOFs each. Its ears can be lowered and elevated while they can point the ear's opening separately. To reduce complexity and the total number of DOFs, these two motions are combined in Probo's ear motion. Figure 11 shows the working principle. By placing the output shaft of the NBDS properly, the rotation that elevates and lowers the entire ear, and the rotation to point the ears opening around, can be combined in one rotation. That way the ear's opening will point to the front when the ear is elevated and the ear's opening will point toward the ground when the ear is lowered to the back of the head. Some examples of different ear positions, and concepts to clarify the principles, are presented in Fig. 12.

3.4.4. Mouth (3DOF)

According to the FACS, there are different AUs (12, 13, 14, 15, 16, 17, 18, 20, etc.), which refer to the region below the nose. It is clear that the mouth plays an important role in facial expressions. Since it would lead to a very complex system, when all these AUs would be implemented in Probo's mouth, various AUs are

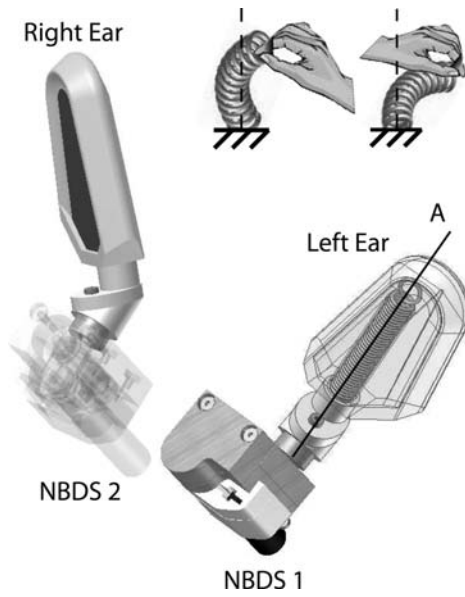


Fig. 11. Transparent detailed view. The helical spring allows deviations in all directions around the centerline.

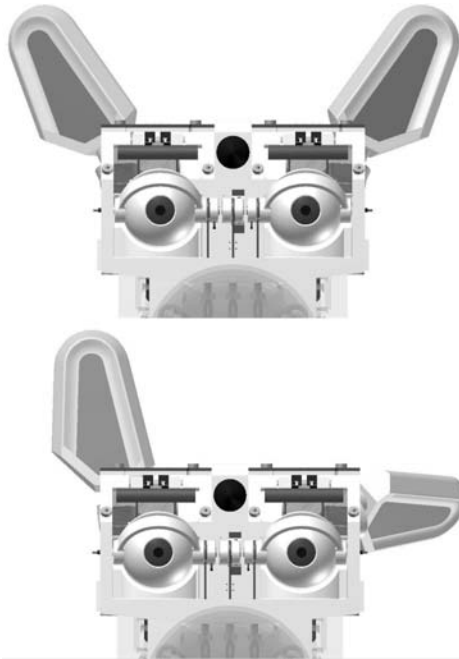


Fig. 12. Some examples of different possible ear positions.

grouped in Probo’s facial mechanisms. However, the movements of Probo’s mouth were designed to roughly mimic AUs 12, 15, 17, and 26, since these are necessary to express emotions such as happy, sadness, and surprise. No further AUs were put in the design of the mouth, since the trunk of Probo limits the visibility of the mouth during operation. For this reason, the mouth of Probo was designed rather big. It is integrated in the lower part of the head, and the mouth corners are visible from the left and right sides of the head (Figs. 13 and 14). Besides the feature of showing facial expressions, the mouth can be used to reinforce the live-like behavior by lip syncing, since Probo will be equipped with speech.⁴⁸

The main part in Probo’s mouth-system is its flexible silicon mouth. This part is not visible in the CAD-models presented in figures, but it is clearly visible in Fig. 5. The entire mouth-system has three DOFs. Each mouth corner is actuated by an NBDS. Probo’s *Upper lip* is constrained by the structure. The *lower lip* can

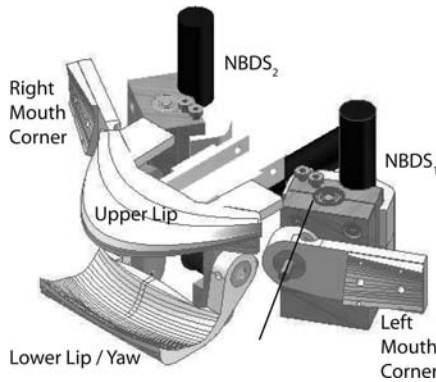


Fig. 13. Front view of CAD model. Two NBDSs are used to actuate the mouth corners.

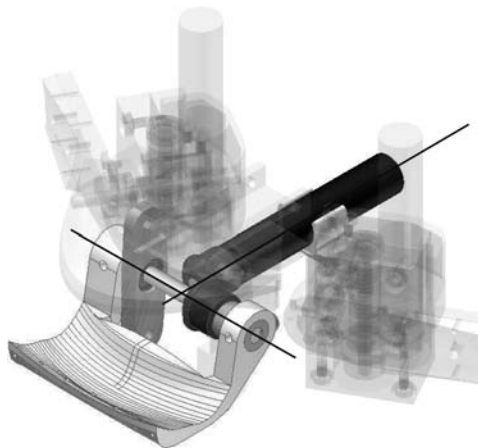


Fig. 14. Transparent front view of CAD model to illustrate the yaw mechanism.

rotate and is connected to the *yaw* motion, since it moves the entire chin of Probo's head. In order to do so, a motor-combination with a reduction is used that drives a one-to-one bevel gear set.

3.4.5. Trunk (3DOF)

A unique facial part, in comparison with other robotic heads, is Probo's intriguing trunk (Figs. 15 and 16). The actuated trunk is used to get the child's attention. Children can easily grab the flexible trunk, to play around. When the child is playing with the trunk, the child's face fits within the scope of the on board camera. This enables face-to-face communication. According to the FACS, there are two main AUs, concerning nose movements, namely AUs 9 and 11. Since a human nose is absolutely not comparable with the trunk of Probo, it is hard to presume that these AUs can be mimicked. However, considered the size and the visual impact of the trunk, it is clear that the trunk must have an influence in the facial behavior of Probo. Probo's trunk has three combined DOFs. The main parts in the system are the *foam core* trunk itself, the *flexible cables*, and the *NBDSs*. This core consists of 10 discs. These discs are constrained to the centerline of the core. Through the discs, parallel to the centerline of the core, three flexible cables are guided through hollow

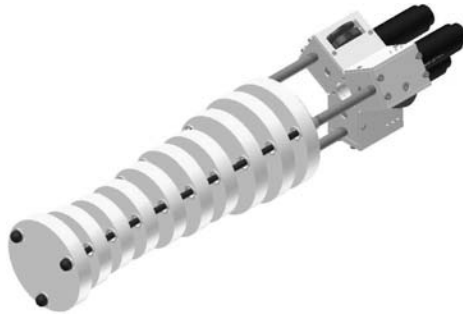


Fig. 15. An overview of the trunk-system.

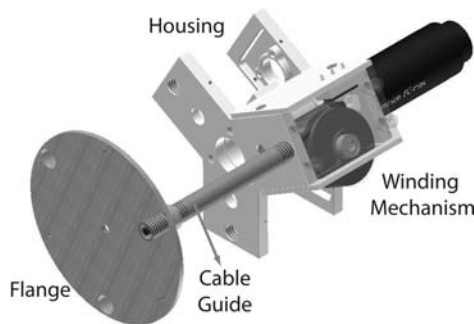


Fig. 16. The mechanism in the housing, which support two additional analogous actuation systems.

bushes. These hollow bushes are constrained to the discs. Since the trunk's core and cables are flexible, the trunk-system is flexible and gives a safe and huggable characteristic.

3.4.6. Neck (3DOF)

All previous described expressive systems are assembled in Probo's head. This head is supported by a three-DOF neck-system, presented in Fig. 17. The three DOFs are all rotations of the center of gravity of the head around axes that are intersecting in a coincident point (*origin* of the X - Y - Z coordinate system). The three rotations are described as:

- (1) roll around X -axis; in this scope referred to as bend or cant motion confer the lateral flexion-extension, or bending of the head (Fig. 18).
- (2) pitch around Y -axis; here called, nod motion confer the flexion-extension of the head (Fig. 19).

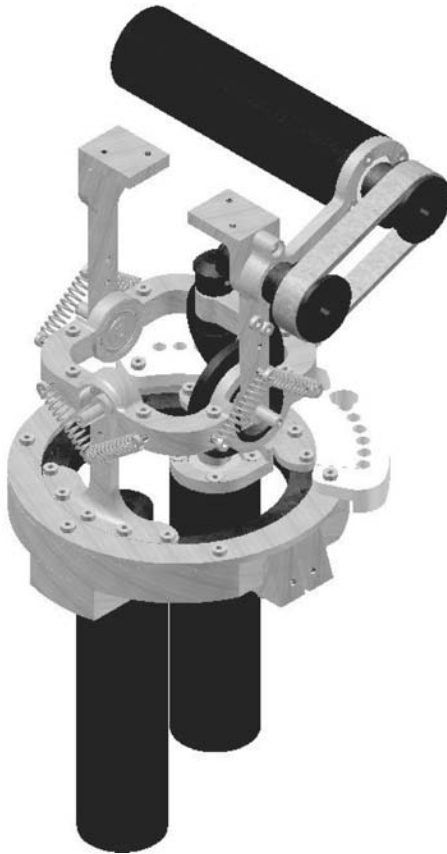


Fig. 17. An overview of the neck-system.

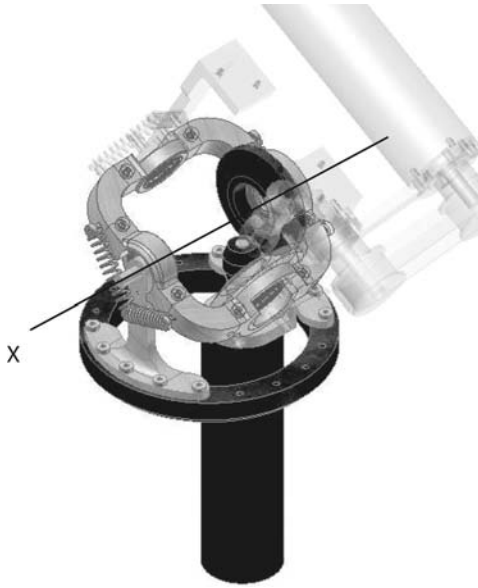


Fig. 18. A detailed view of the bend mechanism. The upper part can rotate relatively from the lower part around the X -axis. In this situation, it is canted over 30° .



Fig. 19. A detailed view of the nod mechanism. The blue part can rotate relatively from the red part around the Y -axis.

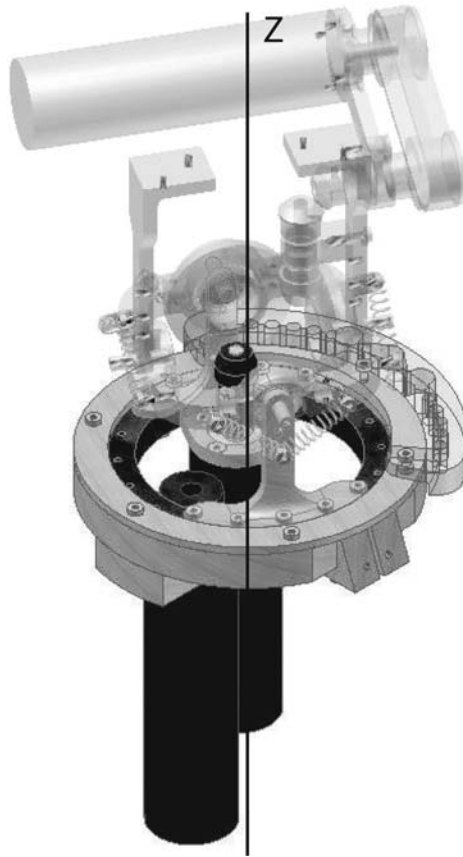


Fig. 20. A detailed view of the rotate mechanism. The dark middle internal gear can rotate relatively from its supporting housing around the Z -axis. In this situation, it is rotated over 60° .

(3) yaw around the Z -axis; here called, rotation confer the axial rotation of the head (Fig. 20).

With these three DOFs, one can mimic AUs 51–56, according to the FACS. These motions require powerful actuators, since the head is the heaviest assembly to move. The actuators must be able to bend, nod, and rotate the entire head, which will be covered by fur, at acceptable speeds, in order to give the impression that Probo is a living creature. To reduce the motor size and consequently make the system lighter and safer, a parallel spring mechanism is installed to perform gravity compensation. In this prototype, the springs are only used to compensate gravity. None of the three axes has compliance yet. Though, this will be integrated in the next generation of neck system. Despite the lack of compliance in the system, the head is protected against the event of uncontrollable robot behavior, since there are mechanical limits, and limits in range controlled by the low-level motor drives. Furthermore, the three

motors in the neck system are all backdrivable and their operational speeds are relative low, which ensure that the impact forces are acceptable at all times.

3.5. *Frame and covering of Probo*

Probo's expressive systems are mounted on an aluminum head-frame. Together they form the head of Probo. The head is supported and actuated by the neck-system. The head-neck-assembly is mounted on its turn on an aluminum body-frame. Both frames are made out of lightweight standard aluminum extruded profiles with L-, T-, or U-shapes. These profiles are easy to manufacture and to adapt. For instance, with conventional manufacturing tools, the profiles can be drilled. These drilled holes can be tapped on their turn to allow screw connections. The expressive systems are all attached to these frames. The assemblage of the (sub)systems themselves and their connection to the frames can be done by the use of a limited set of tools, which includes metric *Allen* wrenches, ranging from *M2* till *M4*, and standard flat and cross screwdrivers. This approach of designing, leads to a user-friendly construction and facilitates maintenance.

In order to obtain Probo's final shape and appearance, the internal robotic hardware is covered. The covering exists of different layers. Hard ABS covers shield and protects Probo's internal hardware, shielding the internals. These covers are fixated to the head and body-frames at the different points. The covers roughly define the shape of Probo. These are manufactured by the use of rapid prototyping techniques, which means that the parts are built layer by layer. These covers are encapsulated in a PUR foam layer, that is covered with a removable fur-jacket. The fur-jacket can be washed and disinfected and complies to the European toy safety standards EN71-1, EN71-2, and EN71-3. The use of the soft actuation principle together with well-thought designs concerning the robot's filling and huggable fur is both essential to create Probo's soft touch feeling and ensure safe interaction.

3.6. *Perceptual system*

In order to interact in a social way with humans, Probo will have to sense its environment in a human way. Since Probo's focus lies on nonverbal face-to-face communication and since it wants to enable physical interaction by its huggable appearance, Probo is equipped with visual, auditory, and tactile perception systems. Following the modular design strategy, the sensors, which are required to sense Probo's environment and physical interactions, are stand alone systems.

- *Visual*: To perceive the environment visually, Probo is equipped with a CCD camera. Probo's camera is mounted between the eyes.
- *Auditory*: The straightforward solution to detect auditory signals is microphones. However, the mixture of surrounding sounds makes appropriate audio processing a challenging job. For instance, in order to improve the audio processing, lavelier

microphones, worn by the interactant, can be used during communicative interaction. Currently, the auditory systems of Probo are under further development.

- *Tactile*: Touch is the most developed sensory modality when we are born and it continues to play a fundamental role in communication throughout the first year of our life. The sense of touch is rather unique: the skin is the largest organ in the human body. A straightforward solution that can imitate the human sense of touch is yet to be discovered. Under the skin of Probo different force sensor resistors are placed. The different body parts of Probo that can sense a touch interaction include: the left ear, the right ear, the top of the head, the trunk, the chest, the left arm, and the right arm. The tactile analysis of the perceptual system of the software platform of Probo is able to detect *pleasant touch*, *normal touch*, and *unpleasant touch*.

4. Quantitative Data and Experimental Results

4.1. Summary of the motor specifications

Table 5 summarizes Probo's degrees of freedom (*DOFs*), the representative *AUs*, the maximum *ranges* of the actuated joints, the nominal *speeds* (n) and *torques* (τ) of the system, the *transmission ratio* of: (i) the custom-made systems (i_s); (ii) the total transmission ratio (i_{tot}), the estimated *efficiency* of the entire transmission (η), and the either geared or not geared motor-encoder-combination. The transmission of the motor-combination is indicated between brackets. The type of the *motor* and its nominal power is based on the *maxon Program 07/08* datasheets. For instance, RE13 represents a DC-brushed motor with a diameter of 13 mm, and ECpowermax22 represents a DC-brushless motor with a diameter of 22 mm. All motors are equipped with incremental magnetic encoders. The nominal resolution is defined by the number of square pulses on a channel per revolution, given in counts per turn (*cpt*). Since the encoders have two channels (and some have even an additional index-channel), the actual resolution is four times higher due to the fact that the number of state transitions (high versus low signals and vice versa) in both channels are counted. These state transitions are called quadcounts (*qc*). The number of *cpt* is indicated in the table as well. One can use them to calculate the resolution of each *DOF*.

Since incremental encoders are used the absolute position of the different *DOFs* is lost when the robot shuts down. During startup of the robot, the calibration procedure begins. This procedure, to find the absolute position, is also referred to as *homing* and is mostly performed by a segmented homing disk attached to the output shaft of an actuated joint and an IR emitter-receiver. Some *DOFs* are manually homed, which in the future can be replaced by measuring the current (done by the EPOS motor controllers), which will significantly increase when touching the end limits. The calibration procedure can be avoided when the robot is disabled earlier in the well-known neutral position. By the use of Bowden cables, problems may occur concerning loosening of cables, friction, and hysteresis. The hysteresis

Table 5. Summary specifications expression and motion systems.

DOF	AU	Range [deg]	Speed [rps]	Torque [Nm]	$i_s/t_{tot}/\eta(\%)$	Motor-combination (i_m) + type (P) + (cpt)
Left eye pan	61, 62	134	6, 10	0,0342	(0,42:1)/(28,1:1)/50	(67:1) + RE13(3W) + (128cpt)
Right eye pan	61, 62	134	6, 10	0,0342	(0,42:1)/(28,1:1)/50	(67:1) + RE13(3W) + (128cpt)
Left eyelid	5, 43, 45, 46	140	1,44	0,145	(1,78:1)/(119,1:1)/50	(67:1) + RE13(3W) + (128cpt)
Right eyelid	5, 43, 45, 46	140	1,44	0,145	(1,78:1)/(119,1:1)/50	(67:1) + RE13(3W) + (128cpt)
Eyes tilt	63, 64	90	1,44	0,145	(1,78:1)/(119,1:1)/50	(67:1) + RE13(3W) + (128cpt)
Left inner eyebrow	1, 4	20	8,26	0,0253	(0,31:1)/(20,77:1)/50	(67:1) + RE13(3W) + (128cpt)
Left outer eyebrow	2	20	8,26	0,0253	(0,31:1)/(20,77:1)/50	(67:1) + RE13(3W) + (128cpt)
Right inner eyebrow	1, 4	20	8,26	0,0253	(0,31:1)/(20,77:1)/50	(67:1) + RE13(3W) + (128cpt)
Right outer eyebrow	2	20	8,26	0,0253	(0,31:1)/(20,77:1)/50	(67:1) + RE13(3W) + (128cpt)
Left ear		120	2,09	0,100	(20:1)/(82:1)/50	(4,1:1) + RE13(3W) + (128cpt)
Right ear		120	2,09	0,100	(20:1)/(82:1)/50	(4,1:1) + RE13(3W) + (128cpt)
Left mouth corner	12, 15	50	0,128	1,63	(20:1)/(1340:1)/50	(67:1) + RE13(3W) + (128cpt)
Right mouth corner	12, 15	50	0,128	1,63	(20:1)/(1340:1)/50	(67:1) + RE13(3W) + (128cpt)
Lower lip/yaw	17, 26	50	2,56	0,155	(1:1)/(67:1)/95	(67:1) + RE13(3W) + (128cpt)
Trunk cable 1	9, 11	60	13,5	0,552	(20:1)/(20:1)/60	ECpowermax22(90W) + (128cpt)
Trunk cable 2	9, 11	60	13,5	0,552	(20:1)/(20:1)/60	ECpowermax22(90W) + (128cpt)
Trunk cable 3	9, 11	60	13,5	0,552	(20:1)/(20:1)/60	ECpowermax22(90W) + (128cpt)
Head nod	53, 54	60	2,72	3,67	(3:1)/(54:1)/80	(18:1) + RE30(60W) + (256cpt)
Head bend	55, 56	60	2,72	4,13	(3:1)/(54:1)/90	(18:1) + RE30(60W) + (256cpt)
Head rotate	51, 52	120	2,10	4,90	(3,55:1)/(64:1)/90	(18:1) + RE30(60W) + (256cpt)

of the CBCDA mechanisms is rather limited, and since high precision is not a strict demand, the calibration procedure suffices, without extra compensation, to determine the desired positions. A friction model and bandwidth tests are described in earlier work.⁴⁴

4.2. *Recognition of emotions*

Recognition experiments of the emotions were conducted and described in Ref. 38. An overall recognition rate of 84% was achieved. In comparison with recognition of human facial expressions, the overall recognition rate is equal. When the robot was not covered, it became more difficult to recognize due to the mechanical look and the absence of a skin. This means an artificial skin or fur is important for a social robot. Like in all the robotic projects, the recognition of fear in facial expressions tends to be the most difficult. When compared with other robots as EDDIE,⁸ Kismet,² Aryan,[?] and Felix,²⁹ better recognition rates were obtained for Probo. Reason is that they did not cover their hardware with a fur or skin, resulting in a mechanical look, making it more difficult to extract the facial features.

4.3. *Live performances and events*

During the development phase, Probo has met dozens of student groups, school-girls and -boys, children, etc., who were visiting the lab. The start of the Probo project and the outcome of the first Probo prototype were announced with two press releases. Regarding the massive interest of national and international press and the numerous reports on Probo, one of the additional goals of Probo to be an attraction pole for the media to communicate science and technology can be seen as effected. A list of appearances in written press, radio, and television can be found at the project's Website <http://probo.vub.ac.be/press/>. Moreover, on the internet, there were extensively reports on the robot Probo in blogs and other news channels. An overview here is difficult to make. Afterwards the robot is invited in several television productions such as science news and popular entertainment shows with scientific background. Probo was even presented in the Belgian pavilion of the Chinese 2010 Expo in Shanghai. Probo was also presented twice at Campus Party, one at Valencia and the other at Sao Paulo. Campus Party is the largest Internet event in the world in the areas of innovation, creativity, science, and digital entertainment. For seven days, thousands of young people live surrounded by a unique and wonderful environment. Born in 1997 as an event for enthusiasts of the internet, campus party has grown to become an unmissable event for understanding new information technology.⁵⁰ Considering the great public interest in Probo on scientific events, and the numerous students who were working spontaneously and devoted on small projects related to Probo, an additional goal of Probo to stimulate and popularize technology and science can be seen as accomplished as well. During these public events, it became clear that in general Probo is well accepted by children, adolescents and adults. Children become strongly attracted by Probo

and show social behavior aiming at interaction and communication. For instance, they speak to Probo, they wave hands, they hug Probo, etc. In this scope, new interaction studies have been set up. For instance, Probo is used in a Romanian autism center as story-telling agent for ASD children. The social stories were tailored to autistic individuals to help them understand and behave appropriately in social situations. In this study, we showed that social story telling with Probo is more effective than with a human reader.⁵¹ During these demonstrations, children could encounter Probo. No safety problems or technical problems were reported during the interaction between Probo and the children. The Probo robot platform has traveled overseas several times, and was approximately 250 h operative, before minor problems occurred, which were all solved by small revisions.

5. Conclusion

The development and construction of the first prototype of the huggable robot Probo are finished and presented in this paper. Probos mechanical systems and software components are operational. Demonstrations of Probo can be found on the projects Web page: <http://probo.vub.ac.be>.

Since Probo is communicative and informative, since it has a safe design and a huggable appearance, and since it has a child-friendly background, it is appropriate to use Probo with children. Since it is modularly designed in terms of hardware and in terms of software, since it is built in a user-friendly way, and since it is expandable and adaptable, Probo is a physical platform that is accessible to researchers with different backgrounds and ready to be used in human-robot interaction studies.

Future plans of the Probo project include the improvement of the look of Probo. The fur and the way it is integrated into the whole system should be reviewed. Further tests must reveal its reliability and robustness. The next generation of Probo robots could be equipped with articulated arms, hands, and body in order to foresee in gestures, manipulations, and poses besides facial expressions.

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