Robotics and Autonomous Systems 63 (2015) 230–243

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

journal homepage: www.elsevier.com/locate/robot

Artificial skin and tactile sensing for socially interactive robots: A review

David Silvera-Tawil [a,*], David Rye [b], Mari Velonaki [a]

[a] Creative Robotics Lab, The University of New South Wales, Australia

[b] Centre for Social Robotics, The University of Sydney, Australia

HIGHLIGHTS

- We present a review of tactile communication for socially interactive robots.
- Diverse approaches to touch sensing for socially interactive robots are discussed.
- An overview of data transmission and calibration methods is presented.
- Current work in touch interpretation for socially interactive robots is reviewed.

ARTICLE INFO

Article history:
Available online 28 September 2014

Keywords:
Sensitive skin
Human–robot interaction
Tactile sensing
Social robotics
Tactile communication

ABSTRACT

During social interaction humans extract important information from tactile stimuli that enriches their understanding of the interaction. This process depends, however, not only on the underlying characteristics of touch, but is influenced by factors such as the context of the interaction, together with the cultures, beliefs and emotions of the individuals who are communicating. The development of a similar capacity in a robot – to "understand" the intended meaning of touch – has the potential to significantly improve the future success of intuitive human–robot interaction. This paper reviews the state-of-the-art in interactive touch and tactile sensing for socially interactive robots.

1. Introduction

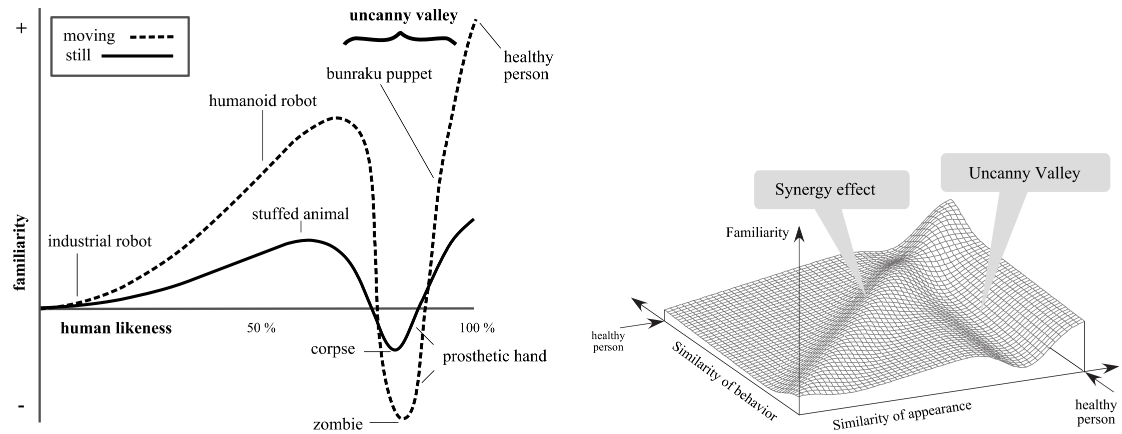
For some time now there has been research directed towards building robots that can interact with humans [1,2]. A pioneering project involved developing the "whole arm manipulator", or "WAM" [3], a robotic arm that was able to sense contact along its whole length, and yield to pressure when it came into contact with obstacles (or humans). Since this early work, robotics research directed towards human–robot interaction (HRI) has fallen into two main areas: humanoid robotics [4–11], and devices typically described in the robotics literature as "robots for psychological enrichment" [12–26].

The fundamental premise of researchers who work in the field of humanoid robotics is that machines (robots) that are designed to operate in social spaces should have capabilities that are "human-like". The intent is to match robot attributes, such as size, strength and dexterity, to tools and structures in the human environment. It is often assumed – perhaps uncritically – that a person will be more psychologically comfortable with a human-like robot. Doubt is cast on this assumption, however, by Mori's theory of the "uncanny valley" [27]—the paradoxical feeling of strangeness when one views a human-like entity that is "not quite perfect".

Although early work in humanoid robotics involved the creation of robots that were, paradoxically, very machine-like in their rigid appearance and behaviour, there is growing awareness in the robotics community of the importance of aspects such as appearance, tactile feel and "social" behaviours of humanoid robots. There is evidence in the literature [28] that any mismatch between a person's expectation of a robot's appearance and behaviour, and the robot's actual appearance and behaviour is a potent source of negative feelings towards the robot. If a machine's appearance and behaviour closely resembles that of a human, our expectation is that it will exhibit human-like characteristics such as intelligence and emotion [29,30]. Mori's theory of the uncanny valley [27], extended by Ishiguro [31], predicts that there is a point where the lack of "something" produces a negative familiarity that results in dislike and rejection (Fig. 1). It is, after all, practically impossible to

* Corresponding author. Tel.: +61 2 8936 0510.
E-mail addresses: dsil8780@uni.sydney.edu.au, d.silverat@unsw.edu.au (D. Silvera-Tawil).

http://dx.doi.org/10.1016/j.robot.2014.09.008
0921-8890/



(a) Mori's uncanny valley.

(b) Ishiguro's extended uncanny valley.

Fig. 1. The uncanny valley according to Mori (a) and to Ishiguro (b).
Source: From [27,31] respectively.

make a replica of a human, and the consequent mismatch between expected and actual behaviour will often raise feelings of repulsion and disapproval.

Roboticists and social researchers are also beginning to appreciate the importance of social, emotional and ethical issues raised by the development of humanoid robots. For example, recently there has been provocative work on social and moral relationships [32–34]; mental models and shared grounds [35]; emotional interaction [36]; the concept of "personal space" [37]; and long-term social interaction [38,39] between a human and a robot. Other work has been focused on human-like appearance and behaviours through the construction of "androids" [31,40] – humanoid robots with a very human-like appearance and more human-like movement – and "geminoids" [41]—androids that could function as a duplicate of an existing person.

Robotic devices aimed at "psychological enrichment" usually take the form of an animal, doll, or pet, such as Paro the robotic seal [12,19,21,23], the Haptic Creature [17,20,26,42], CHARLIE [24], or Huggable the teddy bear [16,18]. These devices aim to first recognise some aspect of a human user's mental state by measuring how they handle the device, and then to respond in some physical way. There is also interesting related work on The Hug [13], a cushion-like form that mediates physical interaction between people in different locations.

As interactions between humans and robots become more complex, there is increasing interest in building robots that can interact with humans in more intuitive and meaningful ways [43]; robots such as the Fish–Bird wheelchairs [44], Robota the humanoid doll [15], KASPAR [22,25,45], and Paro the robotic seal [12,46] have demonstrated that people naturally seek interaction through touch and expect even inanimate-looking robots to respond to tactile stimulation. In robotics, it is therefore important to design a method for touch identification that can be active over all or most of the robot's surface area; this could be achieved using an artificial "sensitive skin".

The functional requirements of an artificial sensitive skin remain debatable and are, to some extent, dependent on the application that the skin is intended for. In the literature, an artificial sensitive skin[1] is usually considered to be a flexible [47,48], stretchable [49] array of sensors that fits onto curved robot surfaces of substantial extent. It may have the ability to sense tactile information such as pressure [50], texture [51], and temperature [52]. In some cases, multiple layers of heterogeneous sensors are used in an attempt to more closely imitate the capabilities of human skin [53,54]. Additionally, soft and silicone-based materials have been used to cover the sensors, to improve wettability and friction properties [55], to increase the contact area, and to give a more "pleasant" feel [12,31,52,56].

The interpretation of touch in robotics and, in particular, via a sensitive skin is a vast, unresolved research area that will play a crucial role in the further development of human–robot interaction (HRI). A robot that is able to "feel", "understand" and respond to touch in accord with human expectations could lead to more meaningful and intuitive HRI. In previous publications we have seen reviews in the area of human–robot interaction [2], socially interactive robots [1], tactile sensing for robotics [57], and tactile human–robot interaction [58]. This article extends those works by focusing particularly on tactile sensing, artificial skin and tactile interaction in socially interactive robots.

In the absence of extensive work in robotic touch the design of touch sensors and, in particular, a robotics sensitive skin is generally guided by a broad knowledge of how information is acquired, encoded and transmitted at various stages of the human sense of touch. In this vein, Section 2 begins with an introduction to the human sense of touch. Section 3 then presents an overview of human-based tactile communication. A review of the state-of-the-art on tactile sensing and artificial sensitive skin for socially interactive robots is introduced in Section 4. Touch interpretation in social human–robot interaction is reviewed in Section 5, followed by a brief discussion and conclusions in Section 6.

2. The human sense of touch

The skin is the largest of all human organs [59]. It gives us the sense of touch, the first sense to develop *in utero* and (arguably) the most important of all human senses [60,61]. Our bodies are literally covered by a huge network of touch receptors and processing centres – the somatosensory system – that allow the perception of temperature changes, pain and irritation, kinaesthesia,[2] touch and vibration; our muscles, joints and organs are all connected to nerves that constantly send information to the brain.

The somatosensory system comprises two different subsystems: cutaneous and kinaesthetic [62,63]. The cutaneous subsystem involves physical contact with the outer surface of the body

[1] The terms "artificial sensitive skin", "artificial skin", "sensitive skin", and "robotics skin" will be used interchangeably when referring to an artificial sensitive skin for robotics applications.

[2] The sense of muscular effort that accompanies a voluntary motion of the body.

and generates sensory inputs through receptors embedded in the skin. The kinaesthetic subsystem receives sensory inputs from receptors in muscles, tendons and joints, and provides information about the position and movement of the body and limbs. Typically, the term "tactile" is used to describe conditions affected by the cutaneous subsystem alone, while the term "haptic" is used to describe inputs that combine both the cutaneous and kinaesthetic subsystems. For the purposes of this review, however, all perception derived from cutaneous and/or kinaesthetic systems is referred to as touch or tactile sensing.

Touch can be classified as a *distal* or *proximal* [64] sense.[3] The former occurs when an object activates touch receptors without having direct physical contact with the skin; for example, through radiation of heat. The later requires direct contact between the object and the skin.

Moreover, touch is also classified in terms of its purposive nature [62,64]. If the human has control over the exploration process and seeks information by moving or touching an object, this is termed *active touch*. In contrast to active touch, and in a manner similar to sight and hearing, if the skin receptors are activated by a moving object touching the surface of the body; this is referred to as *passive touch*. Active touch is often studied in the context of texture recognition [65–69], grasping and object manipulation [70–77]. This review is focused primarily on proximal, passive touch present between humans (human touch received by humans) and, in later sections, between humans and robots (human touch received by robots).

2.1. The physiology of human skin

Human skin is an active sensory organ that is both highly sensitive and highly resilient. It protects our bodies from dehydration, physical injury, toxic substances and ultraviolet radiation. It is waterproof and helps to regulate body temperature, water balance and salt metabolism. It can be touched, vibrated, stretched, compressed, sheared or indented and, without doubt, is critical for touch perception [59,78].

Human skin (Fig. 2) consists of three major layers: epidermis, dermis and hypodermis (or subcutis) [59,63]. The epidermis is the outer layer of the skin that forms the waterproof protective surface and helps to regulate body temperature. The dermis lies beneath the epidermis and contains many nerve endings, sweat glands, apocrine glands, sebaceous glands, lymphatic vessels, hair follicles[4] and blood vessels. The dermis is responsible for conveying nerve signals from thermal, mechanical, chemical and electrical stimuli. Finally, the hypodermis – not normally considered to be part of the skin – is a layer of connective tissue and subcutaneous fat that divides the dermis from the underlying body structure of muscle and bone.

A number of different types of tactile receptors that detect different sensations such as touch, pressure, pain and temperature are widely distributed throughout the skin [62,63,81,82]. These receptors are differentiated in terms of their structure, response and sensing characteristics.

Thermoreceptors [63,82,83] are free nerve endings responsible for perceiving temperature changes. Different thermoreceptors are involved in the perception of cold and warm temperatures. As a result, temperatures are perceived through increases or decreases in skin temperature [84]. If an object causes the temperature of the skin to fall, we say that it feels cold. Changes in temperature are noticed more easily when the initial temperature is moderate rather than hot or cold, and when the area of temperature change is larger.

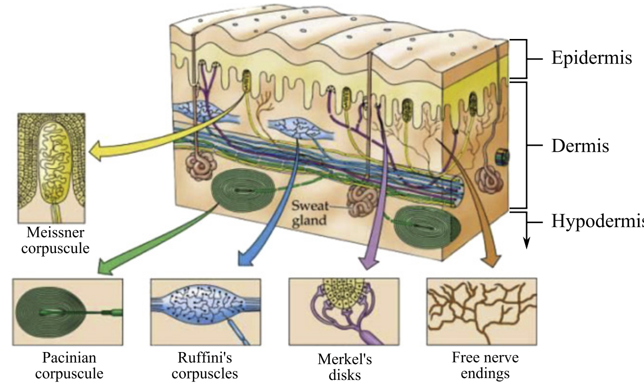


Fig. 2. Touch receptors in hairless (glabrous) skin of the human fingertip. *Source:* Adapted from [80].

Mechanoreceptors [63,80,82,83,85,86] detect physical deformation caused by phenomena such as pressure, touch and vibration. Mechanoreceptors are divided into four different classes distinguished by adaptive response time and receptive field size. Fast adapting units (FA) show rapid responses immediately after physical deformation of the skin. Slow adapting units (SA) show continuous response to sustained deformations. FA and SA units are further divided into "type I" receptors having small receptive fields with sharp borders, and "type II" for large receptors with indistinct borders. Four main types of mechanoreceptors are therefore described:

1. Type FAI: Meissner corpuscles respond particularly well to dynamic skin deformation but provide poor spatial information. They detect low frequency vibrations (20–40 Hz) and are densely packed in the human finger ($\approx$150 units/cm^2).
2. Type SAI: Merkel's discs are responsible for detection and identification of spatial deformations (i.e. corners, edges, curvature) and sustained pressure. They have little sensitivity to stretch and require an almost direct impact to excite. They are approximately 7–90 nm in diameter and are mainly located in the epidermis of glabrous (hairless) skin with approximately 100 units/cm^2 in the fingertip.
3. Type FAII: Pacinian corpuscles are extremely sensitive to small skin motion and are mostly responsible for detecting high frequency (150–300 Hz) stimuli. Pacinian corpuscles respond only at the beginning and end of a touch and are distributed in deep layers of both glabrous and non-glabrous skin. They are approximately 1–4 mm in length and 0.5–1 mm in diameter.
4. Type SAII: Ruffini endings detect intensity, motion, pressure and stretch. They can be found in the dermis and subcutaneous tissue of both glabrous and non-glabrous skin.

Spatial resolution of touch is commonly measured in two different ways [62]. *Point localisation* evaluates the capacity of a person to locate accurately the position of a tactile stimulus. Human sensitivity to touch location varies considerably – from 2 mm to 20 mm – as a function of location on the body (Fig. 3). The *two point discrimination threshold* represents the capacity of a person to discriminate between two simultaneous stimuli. Human two point discrimination ability – 2 mm to 45 mm – also changes as a function of body location. According to Weber [84], stronger pressures mask weaker pressures, and it is easier to discriminate between two touches that do not occur at exactly the same time.

Movement across a surface generates skin vibration which is strongly required for the perception of texture. Katz [87] found that acclimatisation of the skin occurs quickly for motionless touch but not when movement is present.

[3] The terms "distal" and "proximal" are used here in accord with their meanings in cognitive psychology rather than in anatomy. Hence, the visual, auditory and olfactory senses are commonly regarded as "distal", the gustatory sense as "proximal" and the tactile sense as a combination of both.

[4] Hair follicles are found all over the dermis except for load-bearing areas (soles of feet, toes, palms and palmar surfaces of fingers), lips, glans clitoris, labia minora, vestibular aspect of the labia majora and glans penis [59,79].

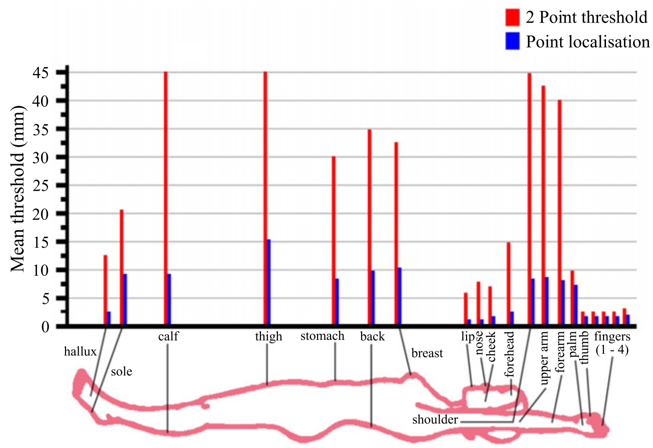


Fig. 3. Point localisation and two point discrimination threshold in human skin. *Source:* Adapted from [62].

Pain and irritation of soft tissue are activated by *nociceptors* [63,83], a different class of nerve endings that respond to extremes in temperature and stimulation, such as thermoreceptors and/or mechanoreceptors exceeding a certain threshold.

In addition, *hair follicle* receptors [82,83] are responsible for sensing the position change of hairs. These receptors adapt rapidly and are the most proficient at detecting initial contact and subsequent movement. Finally *proprioceptors* [83], which are not formally part of the skin but are still considered mechanoreceptors within the somatosensory system, provide information about the position of the limbs.

2.2. *The flow of tactile information*

While many different receptors activate different sensations in the skin, it is rare that just one type of receptor is activated at any one time. For example, when grasping an object, proprioceptors sense the position of the hand and fingers while at the same time mechanoreceptors sense the hardness and smoothness of the material, and thermoreceptors provide information about the thermal conductivity of the material. While these – and probably even more – receptors collect different pieces of information, the somatosensory system needs to transmit all the information to the brain for the stimulus to be perceived. Two main pathways transmit sensory information from the somatosensory receptors to the cerebral cortex: the dorsal column–medial lemniscal pathway and the spinothalamic tract [63,88].

The dorsal column–medial lemniscal pathway [80,89] carries pressure, vibration and joint position information from mechanoreceptors at speeds ranging from 30–120 m/s. The spinothalamic tract [80,89] – which belongs to the anterolateral system – carries pain, temperature, itch and very light (poorly localised) touch signals at much lower velocities ($\approx$0.2–30 m/s).

Both pathways have collateral branches from the spinal cord that mediate autonomic reflex responses and some behavioural reactions to pain. Tactile information is processed at various stages and undergoes a process of selection and adaptation that allows humans to pay more attention to the particular body part that is actively being touched. For additional information on the physiology of human skin and the neuroanatomy of touch, the reader is referred to [80,89–94].

3. Tactile communication

It is believed that – like exercise – people need a daily dose of touch to improve their health and quality of life [78,95–99]. According to [100–102] even casual touch from a stranger can be seen as positive and induce a feeling of wellbeing but, in general, for touch to be positively accepted, it should feel "good".

The interpretation of touch is highly complex and is strongly influenced by the context of the interaction, along with the cultures, beliefs and emotions of the people who are communicating [103]. Early work on social interaction [104,105] demonstrated that humans extract important information from tactile stimuli that helps them to understand the interaction. Humans can be patted, poked, tickled, pushed, hugged and so on, and this can occur in many different social contexts. Stimuli such as these communicate different messages that Heslin and Patterson [105] located within five continuous categories that reflect the level of physical contact, ranging from "unintentional" to "sexual" touch.

It is almost impossible not to respond to touch, yet communication by touch is so powerful that misinterpretation of intentions is potentially harmful. Influencing the interpretation of touch are factors such as the modality of the touch[5] (e.g. pat, push, scratch, etc.), the location of the touch on the body [106], the cultural backgrounds of the two people touching [109], and the content and prosody of any concurrent speech [110].

The location of touch, for example, can be divided into two classes: "non-vulnerable" body parts such as hands, arms, shoulders, and upper back, and "vulnerable" body parts such as head, neck, torso, lower back, buttocks, legs, thighs and feet [111,112]. The more a touch is seen as an invasion of privacy, the less positive – loving, pleasant and friendly – it is rated to be (Fig. 4). According to Nguyen et al. [113] touch perceived in the hands is rated as friendly, loving and pleasant, while touch applied to thighs, buttocks and genitals indicates sexual desire.

Additionally, the congruence between a touch and the context of the interaction in which the touch occurs, and the social intimacy of the people involved in the interaction are all significant factors in the interpretation of and psychological receptivity to touch [106]. For example, in some cultures (e.g. Europe, North and South America), a pat on the buttocks is acceptable between members of a sporting team after a good play, but is considered sexual in more intimate interactions [114]. A pat on the head is often interpreted as condescending, whereas a pat on the back is used to signify congratulations or condolence [115]. The effect of gender is also important. For women, the meaning of a touch is primarily derived from their relationship with the other person. For men, the meaning of a touch is most significantly defined by the other person's gender [106].

We often use touch to share our feelings and enhance other forms of non-verbal and verbal communication [116]. Studies have demonstrated that touch also communicates emotions, and that humans have the ability to distinguish between different emotions transmitted through touch alone [117,118]. Anger, for example, can be characterised by a touch of short duration and moderate-to-strong intensity, such as pushing and shaking, whilst sadness is associated with a light touch of moderate duration, such as nuzzling or hugging. Hertenstein et al. [118] observed that the location of touch on a body varied with the emotion being communicated, and was also dependent on the gender of the touch transmitter and the touch recipient. Prolonged simultaneous touch on more than one body part can often signal a higher degree of intimacy.

Although the aim of touching during human interaction is to communicate messages rather than to transmit touch modalities, human descriptors of touch commonly invoke touch modalities. In other words, it is easier to understand that anger is transmitted

[5] The word modality is often used in the term "sensory modality" to refer to a specific sense (visual, auditory, tactile, etc.). Our usage of "touch modality" here to denote a spatiotemporal pattern of touch is consistent with that previously used in (for example) [106–108].

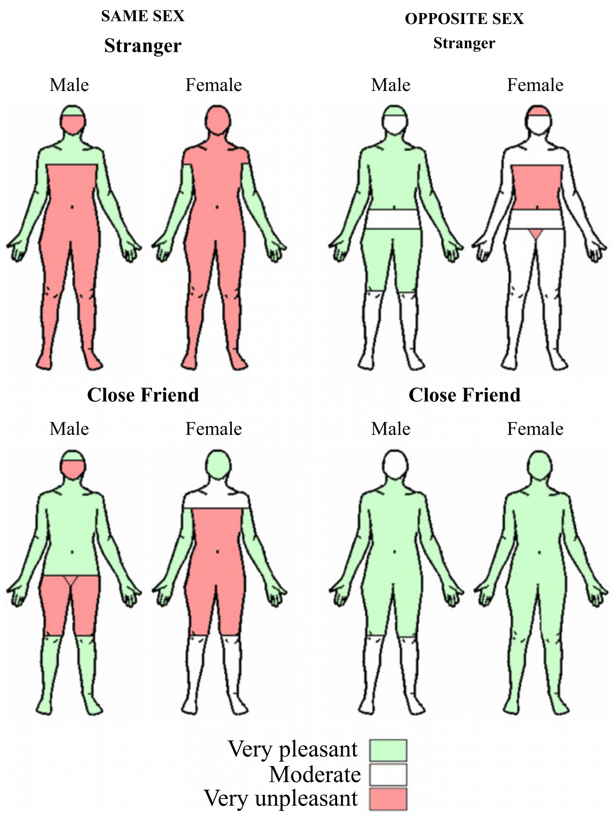


Fig. 4. Rated pleasantness of being touched by another person in different body regions. After Heslin et al. [106].

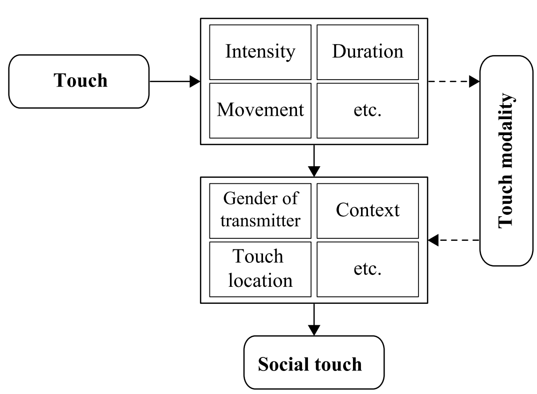


Fig. 5. Conceptual diagram of the interpretation of social touch by a robot [119]. Discontinuous arrows indicate the subordinate role of touch modality interpretation in the interpretation of social touch. This figure suggests that the interpretation of social touch does not necessarily require a prior interpretation of touch by modality.

by "pushing and shaking" than by a "short duration touch of moderate-to-strong intensity". After all, what does moderate-to-strong intensity really *mean*?

The term "touch modalities", as it is used in the present review, refers to the basic form of touch in which a tactile gesture is differentiated only by the spatiotemporal characteristics of the touch itself. Consequently, touch modalities are characterised by attributes such as intensity, movement and duration. The interpretation of social touch (defined as touch that contains social value), however, comprises a more complex process than does identification of a touch modality. Like modality identification, interpretation of social touch begins with the basic characteristics of the tactile gesture, but then aims to "understand" the intended meaning behind the touch. That is, to consider attributes such as body location and context to provide a more accurate and practical interpretation of touch. This process would, for example, allow one to discriminate between a condescending pat and a congratulatory pat by considering which body part the pat is applied to [115].

Although different touch modalities are commonly related to some specific social messages (e.g. stroke with affection, push with rejection, etc. [118,119]), the interpretation of social touch does not strictly require a prior or partial interpretation of touch modality [119], as suggested in Fig. 5. After all, the true aim is to understand the *message*, not the modality used to transmit it.

It is evident that humans extract a wide range of information from tactile stimuli that helps them to interpret touch. In robotics, it is seemingly important to design a method for touch identification and interpretation that allows for both natural and intuitive interactions with humans. This could be achieved using an artificial sensitive skin that is able to provide sufficient information from tactile stimuli to allow the classification of different types of touch. The following section provides a thorough review of touch sensing and artificial sensitive skin for social HRI.

4. Tactile sensing for social HRI

From the first comprehensive elucidation of the concept of artificial "sensitive skin" by Lumelsky et al. [120], researchers have contributed a wide variety of artificial skin prototypes. These usually consist of a number of discrete sensors connected individually or in a grid configuration [121], and which are capable of responding to touch, temperature or other physical phenomena [18]. Approaches to sensing range from the use of organic field-effect transistors (FETs) [122] or piezoresistive semiconductors [123–125] to transducers that use capacitive [126,127], magnetic [128,129], piezoelectric [41,51,54,130–132], optical [133–136] and other principles [137–141]. In some cases, multiple layers of heterogeneous sensors [53] are used in an attempt to more closely imitate the capabilities of human skin. Extensive descriptions of various sensor types can be found in Dario et al. [83], Russell [142], De Rossi and Scilingo [143] and Cutkosky et al. [144], and a study of the state-of-the-art in robot tactile sensing is given by Dahiya et al. [57]. The remainder of this section presents a review of the predominant findings of their work in addition to a discussion of design requirements and fabrication techniques that could make possible a suitably robust and sensitive artificial skin for robotic applications. Note that, although sensing technologies aimed for robot hands and fingers will broadly be mentioned, particular attention will be given to large-scale robotics skins intended for socially interactive robots.

4.1. General design requirements

It is often assumed that the number of sensors distributed over an artificial skin should be large and that the sensors should be small (1 mm or less), especially on hands and fingers [57]. During social HRI, it is particularly important to be able to discriminate between touch from one or multiple fingers (e.g. a "tap") and touch with an open hand (e.g. a "pat") that is applied to the full body of a robot. For this reason, millimetric spatial resolutions are not a high priority and resolutions between 10–40 mm are expected to be satisfactory. Note that these resolutions approximate the two point discrimination threshold of non-glabrous skin areas over large areas of the human body (Fig. 3).

Sensors should be robust, stable, replicable, and capable of detecting a wide range of information. Although a system capable of sensing different types of information in parallel is generally desired [51,52,67,145], this does not necessarily lead to significant improvements in performance. This fact is exemplified by the work of Stiehl and Breazeal [52] in which the use of multiple sensor types such as electric field, pressure and temperature did not provide significant improvements in touch interpretation when compared to other experiments in which only pressure sensors were incorporated [146]. If temperature sensors were to be considered, however, they should be present in lower numbers than pressure sensors. Sensors capable of distinguishing between humans and objects [18] could be particularly beneficial. Both static and dynamic touch should be detected and measured.

Despite the non-linear, hysteretic and time-varying response of human tactile sensing, a linear response with broad dynamic range and low hysteresis is desirable for a tactile sensing system. Typical human touch interactions will range from approximately 0.3 N ($\approx$30 g/cm^2) for a soft stroke to more than 10 N ($\approx$1000 g/cm^2) for a push or slap; in the case of light touch not detected by the force sensors, the inclusion of dynamic (vibration) or proximity sensors would be beneficial. Any touch exceeding 10 N could readily be assessed by other methods such as force/torque sensing in the robot's joints [72,147–149].

Skin fabrication should be simple, low-cost, replicable, scalable and result in durable skin. All hardware should be portable and easily adjustable to different hardware platforms. Electronics should be designed for minimum power consumption and be suitable for battery-powered operation. Electrical noise should be low for good accuracy and repeatability.

The skin should be easily adaptable to various three-dimensional robotic structures. In the case of a humanoid robot, for example, areas such as elbows, knees and shoulders should be covered. In these cases, three-dimensionally flexible and stretchable skins – to approximately 130%–160% of their initial dimensions – could be beneficial. A "single-size" skin that could easily be adapted or cut to the required shape would be ideal [108,135,150]. Alternatively, small independent modular elements that could be placed alongside each other to form different skin shapes would be acceptable [127,150–154]. All sensing capabilities should remain the same regardless of the position of the robot, movement, or skin stretch. Electrical wiring and terminations should be compatible with skin stretch and be kept to a minimum.

To ensure the effectiveness of an artificial skin during social HRI, all hardware should be designed to withstand human-like settings and environments such as extremes and rapid changes of temperature, humidity and moisture, sudden force, stress, dust, light and electric fields. In addition, the appearance and feel of the skin should be appropriate to the robot's appearance and behaviour, given that an unexpected sensation is likely to disrupt any social connection that has been developed. Thus, for an android the look and feel of the skin should be human-like [31,155]. If a soft, protective covering is placed on top or bottom of the skin-like sensor, it may improve various characteristics such as appearance, feel when touched, contact area, collision tolerance, permeability and friction properties [12,31,55,56,67,108,156]. Special care should be taken, however, to assess possible spatiotemporal filtering causing undesirable spatial blurring and/or time delays due to this covering layer. Finally, the skin should be thin so that it does not significantly increase the dimensions of the robot.

All data processing, touch interpretation and decision-making should be done in real time, in particular when it relates to human (and robot) safety [157]. Typically, sampling rates of up to about 1.0–2.5 kHz are desired for tasks such as texture recognition [57,158]. For social HRI, however, frequencies of 20–60 Hz are believed to be adequate [22,108,159]. As with humans (Section 2.1), filtering and adaptability to disregard unnecessary information is acceptable.

Based on the above characteristics, a number of different technologies have been used in endeavours to create better tactile sensors and sensitive skins.

4.2. Tactile sensors and skin-like sensor arrays

The wide variety of sensing technologies used for sensitive skin applications originates in the exploration of different transduction effects and materials. Sensors generally fall into four main categories: force, proximity, temperature and dynamic sensing.

4.2.1. Force/pressure sensing

Measuring force is essentially equivalent to measuring the displacement of a deformable structure due to the application of a localised force or pressure. Pressure sensors should be distributed over the whole body of a robot to detect sustained pressure intensity and movement at relatively low frequencies (20–60 Hz) and spatial resolutions (10–40 mm). These sensors are equivalent to Meissner corpuscles and Ruffini endings in human skin (Section 2.1) and are a high priority for social HRI. Due to their low cost, ease of fabrication and straightforward electronic circuit implementation, mechano-electric sensors, which transform mechanical changes in the materials into electrical signals, are the most common.

Piezoresistive sensors, for example, are made of materials that change their conductivity with applied force [50,160–164]. They are generally sensitive and economic but are often fragile, noisy, and have relatively high power consumption. Due to their availability and easy circuit implementation, force sensing resistors such as those commercially available from Interlink Electronics, Inc.[6] and pressure sensitive rubbers from Tekscan, Inc.[7] have been widely used in socially interactive robots [25,42,123,146,161,165].

Capacitive sensors that make use of the changes in capacitance due to the changes in the distance between two parallel conductive plates have been miniaturised and distributed over the full body, hands and fingers of humanoid robots [45,127,152,166,167]. These sensors have a large dynamic range and are very sensitive to touch. However, they are ill-equipped to manage high strain and can suffer from hysteresis.

Quantum tunnelling composite[8] *(QTC)* sensors are composites of metals and non-conductive elastomers that change their resistance with applied pressure. Although their hysteresis is high, they can easily be cut into any shape without sacrificing their sensing characteristics. The Shadow Hand from The Shadow Robot Company Ltd[9] and Huggable the teddy bear [52] are two reported applications of QTCs.

Finally, *optical sensors* use changes in light intensity to measure pressure and position of touch [134–136,168–173]. Optical sensors are immune to electromagnetic interference, are flexible, sensitive, and have rapid response. Unfortunately, loss of light caused by ruptures and micro-bending may cause major distortions. Optical sensors are often large, bulky, and consume large amounts of power. As far as the authors are aware, the only large-scale applications in which optical sensors have been used for socially interactive robots are [135,159]; note that the former reported currents of up to 50 A in powering a 1000-sensor array.

4.2.2. Proximity sensing

Although proximity sensors do not formally fall into the category of tactile sensing, a number of researchers have employed them for artificial skin applications in interactive robots. The first working prototype of an artificial skin was developed by Lumelsky

6 http://www.interlinkelectronics.com.
7 http://www.tekscan.com.
8 Peratech Ltd., http://www.peratech.com.
9 http://www.shadowrobot.com.

et al. [120] using *infra-red sensor* pairs (IRED + detector). Furthermore, Salter et al. [174] used infra-red sensors in small mobile robots to detect and distinguish human interactions. Although infra-red sensors may be preferable for applications such as collision avoidance [175], their configuration is bulky and easily affected by humidity, water, dust and dirt.

Electric field sensors, on the other hand, use metallic electrodes to measure fluctuations in the electric field. Electric field sensors have been reported in social HRI to detect the proximity of a human hand to a robot [52]. These sensors were used in conjunction with force and temperature sensors to provide information about the qualities of a touch. Electric field systems can be made to be light, small, and power-efficient, but they are easily disturbed by anything that conducts electricity and are ineffective for non-conductive materials.

4.2.3. Dynamic sensing

The ability to sense small movement over the surface of the artificial skin is particularly beneficial during light, dynamic touch (e.g. a "stroke"). *Piezoelectric sensors*, such as polyvinylidene fluoride (PVDF) films [51,54,158] and piezoelectric oxide semiconductor-FETs (POSFETs) [88,176,177], are the most common type of vibration sensors. Piezoelectric materials generate an electrical charge in response to applied force; the output voltage is proportional to the strain velocity. Piezoelectric sensors – like Pacinian corpuscles in human skin (Section 2.1) – are very sensitive to the beginning and end of touch and are ideal for detecting micro-vibration due to small motions across a textured skin.

Piezoelectric sensors are commonly used in the fingers of robotic hands [51,54,67,158,178] but have also been used in whole-body skins of socially interactive robots [31,41,56,179]. Piezoelectric sensors can be made very thin, flexible and extremely sensitive. Their lack of direct current response, the frailty of their electrical junctions, and their thermal sensitivity – which is hard to separate from mechanical effects – are major concerns.

4.2.4. Temperature sensing

Thermal sensing can be used to determine the surface temperature of an object (or a human). Typically, the performance of temperature sensors is reduced by the inclusion of outer protective layers designed to provide a soft surface for the artificial skin. This results in delayed thermal responses that allow temperature sensing only on prolonged contact. In this context, combining temperature with other tactile modalities such as pressure and vibration is desirable. Temperature sensors such as *thermistors* – which have been used in robots aimed at "psychological enrichment" [18,52] – could be effective in detecting body heat from a person holding a robot during prolonged contact (e.g. a hug).

4.2.5. Other sensor types

To address issues of metal fatigue and fragility found in large-scale tactile arrays, conductive rubbers, foams, yarns and fabrics have been used in the fabrication of sensors [126,180,181] and artificial skins for socially interactive robots [119,140,179,182–186]. All of these materials are relatively low cost, flexible and stretchable, easy to manufacture, scalable, and adaptable to any shape. Wiring and electrode connections are complicated, however, and the resulting sensors are often noisy with high hysteresis, are difficult to calibrate and can consume significant amounts of power.

Other approaches use elastomers with electroconductive liquid-filled micro channels [187,188] or conductive gels [189] to measure force and stretch. Unfortunately, these are highly affected by both stretch and pressure, and are prone to rupture, perforation and liquid evaporation.

All flexible sensing arrays are intrinsically vulnerable to stretch, deformation and damage, particularly at wiring terminations. The development of stretchable electronics aims to address this problem [190–193]. At the time of writing, however, the only commercially available large-scale, stretchable sensing array was the "TactArray" from Pressure Profile Systems Inc.[10] This product is comprised of distributed pressure sensors with the ability to stretch up to 10% without degrading sensor performance; no data have been published regarding the performance of this sensor.

Many sensors, particularly those intended for use in hands and fingertips, have been highly integrated and miniaturised as microelectromechanical systems (MEMS) that are generally based on piezoresistive, capacitive or thermal principles [139,194–197]. MEMS-based sensors are quite attractive for robotics applications because of their small size, high accuracy and capability of providing information in multiple transduction modes at high spatial resolutions. However, they are fragile, difficult to fabricate and hard to replicate on a large scale.

As we have seen, many sensing technologies have been investigated. Clearly, every sensing technology has both advantages and disadvantages. The selection of the sensing principal is only the first step in the creation of a skin-like sensor array. All sensors – hundreds or even thousands of sensors – have to be configured. All data from individual and multiple sensory types needs to be acquired, transmitted and combined before it can be interpreted.

4.3. Data transmission

Considering the large amount of information and the desired sample rates, data transmission is generally carried out in stages. In the first stage, multiple sensors are connected to several microprocessors working in parallel and handling the low level, simple and repetitive sensor management. To facilitate this process, the surface area of the skin is often divided into regions (e.g. body parts) with multiple parallel paths asynchronously communicating different information to a centralised unit [18,152,157,189]. Irrelevant information can be filtered out and discarded; for example, if it is determined that a robot "body-part" is not being touched, all data from that part can be rejected. Prioritising of signals that require urgent attention, such as those due to collisions, is essential [157].

At this early stage of the data flow, the number of wires required to transmit data from all sensors constitutes a problem in itself. A large number of distributed wires is not only an excellent antenna for electromagnetic noise, but the flexibility and stretchability of the skin can be reduced by the wires to levels that may impede the dexterity of the robot. A number of approaches have been proposed to solve this problem:

1. Due to their easy realisation *grid-like configurations* with multiplexing electronics were the first reported implementations of array-like sensors [50,53,121]. Unfortunately, these approaches do not scale efficiently for large-scale artificial skins.
2. Sensing modules with one or more sensors (and sensor types) connected to neighbouring modules via single-wire structures or serial buses were implemented in [49,127,135,151–154,198,199]. This technique creates highly modular, intrinsically scalable skins without the need for multiple wires connected to a central unit. It is possible to adjust the area covered by the skin by adding or removing modules. This approach creates arrays that are flexible but unfortunately not stretchable. Although faults due to broken connections between sensing modules are a major concern, Anghinolfi et al. [200] and Buchan et al. [150] improved fault-tolerance by developing algorithms to determine optimal connections between micro-controllers and a set of modules.
3. Stretchable, flexible skin-like sensors based on electrical impedance tomography (EIT) were reported in [108,185,186,201–204]. Since most of the sensing area of EIT-based artificial

[10] http://www.pressureprofile.com.

skins is made of thin materials (e.g. conductive rubbers, foams, fabrics, etc.), it is possible to create large-scale skins of arbitrary shapes and without any – or very limited – internal wiring. Major disadvantages, however, are their poor spatial resolution and their poor ability to discriminate between pressure intensities and contact areas.

4. Wireless data transmission through conductive skin layers connected to individual sensing elements was reported in [49,205–207]. Although the resulting skin will be flexible and stretchable, the interference between the sensing elements and high power requirements could become a bigger issue.

After local "body-part" sensory information is acquired and processed the next stage is to connect all peripheral microprocessors to a central unit designated to run a higher level of interpretation. Here, other sensory modalities such as joint (torque/force) sensors [74,149,208], inertial sensors [149], accelerometers [151,153,154,209], vision [72,159] and even hearing could provide additional information about the interaction with a human. Data transmission at this stage is commonly achieved via a serial bus [18,152,157]. Although transmitting all information serially reduces the number of wires going to the central unit, the detrimental effect of serial communication on transmission speeds is a significant concern.

4.4. Skin calibration

The problem of calibrating a large number of sensors; that is, mapping the location of each taxel in the artificial skin, its correlation with neighbouring taxels and its Euclidean distance to other taxels was investigated by Iwata and Sugano [146] and Noda et al. [179,182], who created two-dimensional representations of the sensory network of an artificial skin and used the resulting network to classify different types of touch. Although these and similar two-dimensional approaches have been effective during the classification of human touch [108,119,210], the reconstructed map does not accurately represent the three-dimensional structure of different robot parts or the location of each sensing elements after the skin is fixed onto a robot.

More recently, Cannata et al. [211] introduced a generic formulation for a three-dimensional self-calibration approach. The principle of this method is that a robot may calibrate its own skin, estimating network topology and the three-dimensional location of each sensor (or sensing module with one or more sensors) by touching known locations on its own body and activating skin sensors in a controlled way [211,212]. Moreover, Mittendorfer and Cheng [153,154] presented a touch-less approach to skin calibration. By following a similar methodology to Hoshi and Shinoda [213], Mittendorfer and Cheng used triaxial accelerometers located within sensing modules in addition to the geometric characteristics of these modules to estimate the three-dimensional location of each module and the network topology after the artificial skin is assembled over any three-dimensional object, such as a robot body-part.

Although significant work is still required before a full-body sensitive skin is successfully integrated with a robot, it is clear that selection of the best skin-like technology requires a compromise between sensing, data transmission and calibration requirements. Considering that during social interaction humans have the ability to understand messages transmitted via touch despite the significant sensory limitations of some areas of human skin (Fig. 3), it can be deduced that a high-performance artificial skin – with, for example, sub-millimetre spatial resolution and sampling rates over 100 Hz – is not necessarily a key factor in improving social HRI through touch. The feel and appearance of the skin, together with its ability to identify static and dynamic touch, are certainly critical for touch interpretation. The following section elaborates further on this area and presents a review of the latest developments in touch interpretation for socially interactive robots.

5. Touch interpretation in social HRI

Even in the early stages of the development of tactile sensing in social HRI, sensing and interpretation of touch has been shown to play an important role, where robots such as Paro the seal [14,19,21,23,214] and the child-sized robot KASPAR [22,25,45] have provided significant physical and mental improvements to child and adult patients. Furthermore, interactive humanoid robots with tactile sensing capabilities illustrate the possibility of using robots to improve daily life, from Robovie [215] working as a tutor in classrooms, to Robonaut 2 [9] collaborating side-by-side with humans as a "team member" in the International Space Station. Although these examples suggest that interpretation of tactile stimuli would be a useful tool in social HRI, methods for tactile sensing and touch interpretation are still far from perfect.

Research in the area of interactive touch has typically been focused around the development of methods for identifying touch modalities [16,108,146,165,209,216] through supervised machine learning techniques. Iwata and Sugano [146,217], for example, used a modified counter-propagation algorithm to classify ten touch modalities, while Stiehl et al. [16] and Stiehl and Breazeal [52] used artificial neural networks to classify eight touch modalities. In both cases touch was transmitted only by a single individual. The *k*-nearest neighbour algorithm was used by Naya et al. [165] to classify five touch modalities transmitted by eleven subjects. Koo et al. [209] used temporal decision trees to classify four easily separable touch modalities from twelve subjects while Silvera Tawil et al. [108] used a LogitBoost algorithm to classify nine modalities transmitted by 40 individuals. In all these cases, touch was transmitted to low-resolution[11] artificial skins and skin-like arrays with as few as nine discrete sensors [209] and the ability to acquire information such as touch location (proximity and force sensors), intensity of touch (accelerometers and force sensors) and displacement of touch (accelerometers and force sensors).

The interpretation of emotions and other social messages has been confined to facial expression [218,219], acoustic information [220], audiovisual data [221], physiological signals [222,223] and touch through ordinary haptic devices, such as a computer mouse [224]. As far as we are aware, the interpretation of social touch for robotics – and in particular through an artificial sensitive skin – has not been widely studied.

Knight et al. [210] used touch information from local force and electric field sensors combined with the location of touch on the robot's body to differentiate between *socially-loaded* touch (e.g. hug, head pat, foot rub, cheek slap, etc.) and touch modalities. *Socially-loaded* touch was defined in [119] as touch that contains some hidden social implication which cannot be interpreted unambiguously without additional information, such as the location of the touch on the body, or the social context of the interaction. Although the work in [210] approached the interpretation of social touch, only socially-loaded touches that were clearly not related to any social message were considered. Similar work, where touch modality and whole-body location were used to classify socially-loaded touch, was presented by Taichi et al. [183].

A number of factors influence the way that humans interpret touch, and most of these factors are related to touch only in indirect ways. In other words, touch interpretation for human–robot interaction cannot depend purely on an artificial sensitive skin. Touch interpretation should work in a harmonious balance with other sensory modalities – for example, sound or speech, vision and proprioception – that can provide more information about the people touching the robot, the environment, and the nature of the touch. With this in mind, Cooney et al. [159] were able to improve

[11] Point localisation accuracy not better than 10 mm.

the classification of socially-loaded touch in a full-bodied robot by using a Microsoft Kinect RGB-D sensor and the OpenNI software framework, in addition to touch sensors, to assess the classification. Classification of touch was done using a support vector regression algorithm. The artificial 'skin' was made of 40 discrete force sensors (of approximate dimensions 60×60 mm and 150×60 mm) sampled at 20 Hz. In addition, and through participants' responses to questionnaires, this work evaluated different levels of affection typically conveyed by 20 different tactile gestures, such as "forehead touch", "back rub", and "cheek slap".

Noda et al. [179,182] proposed a method for touch classification based on scenarios such as "lets shake hands"; "give me a hug"; "I wish you'd pat me on the head;" "hello" and "what's your name?" The robot in this research was controlled using the "Wizard of Oz" methodology [225] while it interacted with humans. Touch features were based on the location and cross-correlation of piezoelectric sensors distributed over the robot's body. The artificial skin was build using discrete PVDF films (of dimension 50×50 mm and 30×30 mm) sampled at 100 Hz. Although this work closely relates to the interpretation of social touch (e.g. "hello"), it is intermixed with socially-loaded touch (e.g. "I wish you'd pat me on the head") and detailed information about the scenarios and the attributes of the touch involved in each scenario was not provided. Furthermore, class labels were assigned on the basis of how the robot approached – as the touch initiator – and spoke to the participants. It is believed that this behaviour could have strongly influenced the way that participants transmitted touch.

Yohanan and MacLean [20,26,226], on the other hand, studied the interpretation and display of affective touch through the artificial Haptic Creature. In [26] Yohanan and MacLean surveyed people to evaluate the likelihood that each of thirty tactile gestures would be used by the participants to communicate nine emotions – taken from Russell's two-dimensional model of affect [227] – to the robotic creature. Each participant then transmitted their most likely touch gestures to the Haptic Creature whilst imagining feeling the emotion that they associated with the touch gesture. The location, duration and pressure of touch were manually encoded second-by-second.

Silvera-Tawil et al. [119] studied the classification of twelve discrete emotions and social messages commonly transmitted by humans via touch. Their experimental results demonstrated that autonomous classification of social touch can be achieved at better-than-chance levels – using an EIT-based artificial skin with force sensing capabilities (at $\approx$40 Hz) – and with accuracies comparable to those achieved by humans. Note that since emotions were not induced during the experiments reported in [26,119], participants could have been communicating emotional intentions rather than emotions. Nevertheless, the experiments provided extensive information about the different gestures that were used to communicate emotions and social messages by touching a robot; for example they both demonstrated that a touch modality such as "squeeze" can be used to convey "excitement", an emotion of high arousal. In addition, both these works demonstrate the importance of the spatiotemporal characteristics of tactile gestures – such as location, area of contact and touch duration – during the interpretation of social touch. Silvera-Tawil et al. [119] concludes that better interpretation of social touch can be achieved by using the underlying characteristics of touch without considering a prior interpretation of touch by modality. Interestingly, no significant dependence of touch classification accuracy on gender or country of origin of the touch transmitters was found.

6. Discussion and conclusions

The development of an artificial skin for robotics is not an easy task. This review began by focusing on a broad understanding of the human sense of touch, the physiology of human skin and human–human tactile communication that will underpin the design of an appropriate sensitive skin for human–robot interaction. Importantly, the purpose of touch during human-to-human interaction – and by extension during social human–robot interaction – is not to transmit different modalities of touch but to convey a message or an intention to the touch recipient. If the same modality of touch is used on different body locations or in a different social context, the recipient may interpret the touch as (for example) open and friendly, condescending, or even sexual.

As discussed in Section 4, robotics researchers are working with many technologies to improve the sensing capabilities of artificial skins. It is believed, however, that a high-performance artificial skin – with, for example, sub-millimetre spatial resolution, multiple sensory modalities, and sampling rates over 100 Hz – is not necessarily a key factor in improving social human–robot interaction through touch, as shown in Section 5.

Many diverse approaches to tactile sensing were discussed to provide an overview of the state-of-the-art in skin-like sensors, data transmission and calibration. A "perfect" solution is not yet available. Latest developments, however, are directed towards a modular approach in which individual modules with one or more sensors are directly connected to neighbouring modules. This approach provides scalable and easily-manufactured solutions with a reduced number of wires and the potential to incorporate different sensors types in each module. Semi-flexible 'skins' are possible by using flexible printed circuit boards while stretchability properties could be achieved by using stretchable wires [190,191]. Furthermore, if soft silicon-like materials are used to cover the skin, it is possible that flexible but not stretchable sensors could be mounted onto rigid robotics structures, and only the outer layer covering the sensors would need to be flexible and stretchable. Special consideration needs to be taken, however, when the skin is used to cover highly-movable parts of a robot, such as robot joints.

If we scrutinise the interpretation of touch through an artificial skin (Section 5) we notice that, to date, most research has focused on touch modality classification using supervised machine learning algorithms. Nonetheless, recent trends suggest an increasing interest in socially-loaded touch, emotions and social messages that can provide additional information about the 'meaning' of the touch. Future work should also investigate semi-supervised machine learning techniques instead of the fully-supervised techniques that are commonly used.

It is important to recognise that human interpretation of touch begins almost immediately following the start of a touch: interpretation does not wait until the touch has ended. Touch interpretation in HRI should therefore also consider temporal classification methods in which the classification can begin before the end of the touch, as proposed by Koo et al. [209] for the classification of touch modalities. Furthermore, even if artificial skins are commonly designed with multi-touch capabilities, most research in touch interpretation ignores the multi-touch effects that occur when a person touches with both their hands simultaneously. For example, touching two body parts simultaneously may be characteristic of more intimate forms of touch [118]. Future research should investigate this multi-touch effect. Multiple sequential touch gestures belonging to the same 'message' should also be investigated.

Different tactile gestures can be expected based on factors such as the appearance, feel and behaviour of the skin (and robot). Given that these factors are important in reducing the uncanny effect that can exist during HRI, special attention should be given to these during the interpretation of touch. The context of the interaction (i.e. experimental setting), gender and cultural factors – such as country of origin and religious beliefs – of the touch transmitter should be taken into account.

Finally, other sensor types, such as vision, audio and kinaesthetic sensing, as in [52,119,159], can be integrated with the existing apparatus to investigate improved methods of social touch interpretation. Ideally, all touch sensing and interpretation systems should be compared with the interpretative abilities of human touch recipients.

References

[1] T. Fong, I. Nourbakhsh, K. Dautenhahn, A survey of socially interactive robots, Robot. Auton. Syst. 42 (2003) 143–166.
[2] M. Goodrich, A. Schultz, Human–robot interaction: a survey, Found. Trends Human–Computer Interact. 1 (3) (2007) 203–275.
[3] J. Guertin, W. Townsend, Teleoperator slave-WAM design methodology, Ind. Robot 26 (3) (1999) 167–177.
[4] B. Adams, C. Breazeal, R. Brooks, B. Scassellati, Humanoid robots: A new kind of tool, IEEE Intell. Syst. Appl. (ISSN: 1094-7167) 15 (4) (2000) 25–31.
[5] C. Atkeson, J. Hale, F. Pollick, M. Riley, S. Kotosaka, S. Schaul, T. Shibata, G. Tevatia, A. Ude, S. Vijayakumar, E. Kawato, M. Kawato, Using humanoid robots to study human behavior, IEEE Intell. Syst. Appl. 15 (4) (2000) 46–56.
[6] J.-H. Oh, D. Hanson, W.-S. Kim, Y. Han, J.-Y. Kim, I.-W. Park, Design of android type humanoid robot Albert HUBO, in: Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems, 2006, pp. 1428–1433.
[7] K. Yokoi, Humanoid robotics, in: Proc. IEEE International Conference on Control Automation and Systems, 2007, pp. lxxiv–lxxix.
[8] N. Endo, S. Momoki, M. Zecca, M. Saito, Y. Mizoguchi, K. Itoh, A. Takanishi, Development of whole-body emotion expression humanoid robot, in: Proc. IEEE International Conference on Robotics and Automation, 2008, pp. 2140–2145.
[9] M. Diftler, J. Mehling, M. Abdallah, N. Radford, L. Bridgwater, A. Sanders, R. Askew, D. Linn, J. Yamokoski, F. Permenter, B. Hargrave, R. Platt, R. Savely, R. Ambrose, Robonaut 2—the first humanoid robot in space, in: Proc. IEEE International Conference on Robotics and Automation, 2011, pp. 2178–2183.
[10] K. Ogawa, K. Narioka, K. Hosoda, Development of whole-body humanoid "Pneumat-BS" with pneumatic musculoskeletal system, in: Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems, 2011, pp. 4838–4843.
[11] Y. Tsumaki, F. Ono, T. Tsukuda, The 20-DOF miniature humanoid MH-2: A wearable communication system, in: Proc. IEEE International Conference on Robotics and Automation, 2012, pp. 3930–3935.
[12] K. Wada, T. Shibata, T. Saito, K. Tanie, Analysis of factors that bring mental effects to elderly people in robot assisted activity, in: Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems, vol. 2, 2002, pp. 1152–1157.
[13] C. DiSalvo, F. Gemperle, J. Forlizzi, E. Montgomery, The Hug: An exploration of robotic form for intimate communication, in: Proc. IEEE Robot and Human Interactive Communication, 2003, pp. 403–408.
[14] T. Shibata, An overview of human interactive robots for psychological enrichment, Proc. IEEE 92 (11) (2004) 1749–1758.
[15] B. Robins, P. Dickerson, K. Dautenhahn, Robots as embodied beings—interactionally sensitive body movements in interactions among autistic children and a robot, in: Proc. IEEE International Workshop on Robot and Human Interactive Communication, 2005, pp. 54–59.
[16] W. Stiehl, J. Lieberman, C. Breazeal, L. Basel, L. Lalla, M. Wolf, Design of a therapeutic robotic companion for relational, affective touch, in: Proc. IEEE International Workshop on Robot and Human Interactive Communication, 2005, pp. 408–415.
[17] S. Yohanan, M. Chan, J. Hopkins, H. Sun, K. MacLean, Hapticat: Exploration of affective touch, in: Proc. International Conference on Multimodal Interfaces, 2005, pp. 222–229.
[18] W. Stiehl, C. Breazeal, A sensitive skin for robotic companions featuring temperature, force, and electric field sensors, in: Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems, 2006, pp. 1952–1959.
[19] K. Wada, T. Shibata, Living with seal robots—its sociopsychological and physiological influences on the elderly at a care house, IEEE Trans. Robot. 23 (5) (2007) 972–980.
[20] S. Yohanan, K. MacLean, The Haptic creature project: Social human–robot interaction through affective touch, in: Proc. AISB Symposium the Reign of Catz & Dogz: the Second AISB Symposium on the Role of Virtual Creatures in a Computerised Society, vol. 1, 2008, pp. 7–11.
[21] K. Wada, T. Shibata, Social effects of robot therapy in a care house—change of social network of the residents for one year, J. Adv. Comput. Intell. Intell. Inform. 13 (4) (2009) 386–387.
[22] B. Robins, F. Amirabdollahian, Z. Ji, K. Dautenhahn, Tactile interaction with a humanoid robot for children with autism: a case study analysis involving user requirements and results of an initial implementation, in: Proc. IEEE International Symposium on Robot and Human Interactive Communication, 2010, pp. 704–711.
[23] T. Shibata, Y. Kawaguchi, K. Wada, Investigation on people living with Paro at home, in: IEEE International Symposium on Robot and Human Interactive Communication, 2010, pp. 470–475.
[24] L. Boccanfuso, J. OKane, CHARLIE: an adaptive robot design with hand and face tracking for use in autism therapy, Int. J. Soc. Robot. 3 (2011) 337–347.
[25] B. Robins, K. Dautenhahn, H. Lehmann, Tactile interaction and imitation games in human–robot interaction studies with children with autism, in: Proc. Workshop on Advances in Tactile Sensing and Touch based Human–Robot Interaction, 2012.
[26] S. Yohanan, K. MacLean, The role of affective touch in human–robot interaction: human intent and expectations in touching the haptic creature, Int. J. Soc. Robot. 4 (2012) 163–180.
[27] M. Mori, Bukimi no tani [The uncanny valley], Energy 7 (4) (1970) 33–35.
[28] M. Shimada, T. Minato, S. Itakura, H. Ishiguro, Uncanny valley of androids and its lateral inhibition hypothesis, in: Proc. IEEE International Symposium on Robot and Human Interactive Communication, 2007, pp. 374–379.
[29] S. Woods, K. Dautenhahn, J. Schulz, The design space of robots: investigating children's views, in: Proc. IEEE International Workshop on Robot and Human Interactive Communication, 2004, pp. 47–52.
[30] F. Hegel, S. Krach, T. Kircher, B. Wrede, G. Sagerer, Understanding social robots: A user study on anthropomorphism, in: Proc. IEEE International Symposium on Robot and Human Interactive Communication, 2008, pp. 574–579.
[31] H. Ishiguro, Android science: towards a new cross-disciplinary framework, in: Proc. CogSci Workshop: Toward Social Mechanisms of Android Science, 2005, pp. 1–6.
[32] J. Wagner, H.V. der Loos, L. Leifer, Construction of social relationships between user and robot, Robot. Auton. Syst. 31 (3) (2000) 185–191.
[33] B. Duffy, Anthropomorphism and the social robot, Robot. Auton. Syst. 42 (3–4) (2003) 177–190.
[34] J. Kahn, P.H., N. Freier, B. Friedman, R. Severson, E. Feldman, Social and moral relationships with robotic others? in: Proc. IEEE International Workshop on Robot and Human Interactive Communication, 2004, pp. 545–550.
[35] J.-H. Hwang, K.-W. Lee, D. Kwon, The role of mental model and shared grounds in human–robot interaction, in: Proc. IEEE International Workshop on Robot and Human Interactive Communication, 2006, pp. 623–628.
[36] R. Arkin, M. Fujita, T. Takagi, R. Hasegawa, An ethological and emotional basis for human–robot interaction, Robot. Auton. Syst. 42 (3–4) (2003) 191–201.
[37] M. Walters, K. Dautenhahn, R. Boekhorst, K. Koay, C. Kaouri, S. Woods, C. Nehaniv, D. Lee, I. Werry, The influence of subjects' personality traits on personal spatial zones in a human–robot interaction experiment, in: Proc. IEEE International Workshop on Robot and Human Interactive Communication, 2005, pp. 347–352.
[38] T. Bickmore, R. Picard, Establishing and maintaining long-term human–computer relationships, ACM Trans. Computer–Human Interact. 12 (2) (2005) 293–327.
[39] R. Gockley, A. Bruce, J. Forlizzi, M. Michalowski, A. Mundell, S. Rosenthal, B. Sellner, R. Simmons, K. Snipes, A. Schultz, J. Wang, Designing robots for long-term social interaction, in: Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems, 2005, pp. 1338–1343.
[40] H. Ishiguro, Interactive humanoids and androids, in: Digest of Technical Papers, 2006 Symposium on VLSI Technology, 2006, pp. 3–6.
[41] H. Ishiguro, S. Nishio, Building artificial humans to understand humans, J. Artificial Organs 10 (3) (2007) 133–142.
[42] J. Chang, K. Maclean, S. Yohanan, Gesture recognition in the haptic creature, in: Proc. International Conference on Haptics: Generating and Perceiving Tangible Sensations, 2010, pp. 385–391.
[43] C. Breazeal, Toward sociable robots, Robot. Auton. Syst. 42 (2003) 167–175.
[44] M. Velonaki, D. Rye, S. Scheding, S. Williams, Fish–Bird: Autonomous interactions in a new media arts setting, in: Proc. Vital Signs: Creative Practice and New Media Now, 2005.
[45] D. Robins, K. Dautenhahn, P. Dickerson, Embodiment and cognitive learning—can a humanoid robot help children with autism to learn about tactile social behaviour? in: S. Ge, O. Khatib, J. Cabibihan, R. Simmons, M. Williams (Eds.), Social Robotics, in: Lecture Notes in Computer Science, vol. 7621, Springer, Berlin, Heidelberg, 2012, pp. 66–75.
[46] W. Chang, S. Šabanović, L. Huber, Use of seal-like robot PARO in sensory group therapy for older adults with dementia, in: Proc. ACM/IEEE International Conference on Human–Robot Interaction, 2013, pp. 101–102.
[47] J. Kim, J. Lee, H. Lee, Y. Park, M. Kim, D. Kang, Design of flexible tactile sensor based on three-component force and its fabrication, in: Proc. IEEE International Conference on Robotics and Automation, 2005, pp. 2578–2581.
[48] K. Kim, K. Lee, D. Lee, N. Cho, W. Kim, K. Park, H. Park, Y. Kim, Y. Park, J. Kim, A silicon-based flexible tactile sensor for ubiquitous robot companion applications, J. Physics 34 (2006) 399–403.
[49] T. Hoshi, H. Shinoda, A sensitive skin based on touch-area-evaluating tactile elements, in: Proc. IEEE Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2006, pp. 89–94.
[50] M. Shimojo, R. Makino, A. Namiki, M. Ishikawa, T. Suzuki, K. Mabuchi, A sheet type tactile sensor using pressure conductive rubber with electrical-wires stitches method, in: Proc. IEEE Sensors, vol. 2, 2002, pp. 1637–1642.
[51] K. Hosoda, Robot finger design for developmental tactile interaction: anthropomorphic robotic soft fingertip with randomly distributed receptors, in: Proc. Embodied Artificial Intelligence, vol. 2865, 2003, pp. 219–230.
[52] W. Stiehl, C. Breazeal, Affective touch for robotic companions, in: Proc. International Conference on Affective Computing and Intelligent Interaction, 2005, pp. 747–754.
[53] R. Lazzarini, R. Magni, P. Dario, A tactile array sensor layered in an artificial skin, in: Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems, vol. 3, 1995, pp. 114–119.
[54] S. Takamuku, G. Gómez, K. Hosoda, R. Pfeifer, Haptic discrimination of material properties by a robotic hand, in: Proc. IEEE International Conference on Development and Learning, 2007, pp. 1–6.

[55] H. Shirado, Y. Nonomura, T. Maeno, Realization of human skin-like texture by emulating surface shape pattern and elastic structure, in: Proc. IEEE Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2006, pp. 295–296.
[56] T. Minato, Y. Yoshikawa, T. Noda, S. Ikemoto, H. Ishiguro, M. Asada, CB^2: A child robot with biomimetic body for cognitive developmental robotics, in: Proc. IEEE-RAS International Conference on Humanoid Robots, 2007, pp. 557–562.
[57] R.S. Dahiya, G. Metta, M. Valle, G. Sandini, Tactile sensing—from humans to humanoids, IEEE Trans. Robot. 26 (1) (2010) 1–20.
[58] B. Argall, A. Billard, A survey of tactile human–robot interactions, Robot. Auton. Syst. 58 (2010) 1159–1176.
[59] A. Williams, Transdermal and Topical Drug Delivery From Theory to Clinical Practice, Pharmaceutical Press, 2003, pp. 1–25. Chap. 1: Structure and function of human skin.
[60] J. Rothwell, M. Traub, B. Day, J. Obeso, P. Thomas, C. Marsden, Manual motor performance in a deafferented man, Brain 105 (1982) 515–542.
[61] G. Robles-De-La-Torre, The importance of the sense of touch in virtual and real environments, IEEE Multimedia 13 (3) (2006) 24–30.
[62] S. Lederman, Skin and touch, in: R. Dulbecco (Ed.), Encyclopedia of Human Biology, vol. 7, Academic Press, 1991, pp. 51–63.
[63] R. Klatzky, S. Lederman, Handbook of Psychology, in: Experimental Psychology, vol. 4, John Wiley and Sons, 2003, pp. 147–176. Chap. 6: Touch.
[64] M. Symmons, Active and pasive haptic exploration of two and three dimensional stimuli (Ph.D. thesis), Monash University, 2004.
[65] N. Jamali, C. Sammut, Majority voting: material classification by tactile sensing using surface texture, IEEE Transactions on Robotics 27 (3) (2011) 508–521.
[66] C.M. Oddo, M. Controzzi, L. Beccai, C. Cipriani, M.C. Carrozza, Roughness encoding for discrimination of surfaces in artificial active-touch, IEEE Transactions on Robotics 27 (3) (2011) 522–533.
[67] J. Fishel, G. Loeb, Bayesian exploration for intelligent identification of textures, Front. Neurorobotics 6 (4) (2012) 20.
[68] V. Ho, T. Araki, M. Makikawa, S. Hirai, Experimental investigation of surface identification ability of a low-profile fabric tactile sensor, in: Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems, 2012, pp. 4497–4504.
[69] H. Liu, X. Song, J. Bimbo, L. Seneviratne, K. Althoefer, Surface material recognition through haptic exploration using an intelligent contact sensing finger, in: Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems, 2012, pp. 52–57.
[70] T. Yoshikawa, M. Koeda, H. Fujimoto, Shape recognition and grasping by robotic hands with soft fingers and omnidirectional camera, in: Proc. IEEE International Conference on Robotics and Automation, 2008, pp. 299–304.
[71] S. Wieland, D. Gonzalez-Aguirre, N. Vahrenkamp, T. Asfour, R. Dillmann, Combining force and visual feedback for physical interaction tasks in humanoid robots, in: Proc. International Conference on Humanoid Robots, 2009, pp. 439–446.
[72] P. Hebert, N. Hudson, J. Ma, J. Burdick, Fusion of stereo vision, force-torque, and joint sensors for estimation of in-hand object location, in: Proc. IEEE International Conference on Robotics and Automation, 2011, pp. 5935–5941.
[73] M. Roa, R. Suarez, Influence of contact types and uncertainties in the computation of independent contact regions, in: Proc. IEEE International Conference on Robotics and Automation, 2011, pp. 3317–3323.
[74] Y. Bekiroglu, R. Detry, D. Kragic, Grasp stability from vision and touch, in: Proc. Workshop on Advances in Tactile Sensing and Touch-based Human–Robot Interaction, IEEE/RSJ International Conference on Intelligent Robots and Systems, in: Lecture Notes in Computer Science, vol. 7559, 2012, pp. 12–13.
[75] T. Bhattacharjee, J. Rehg, C. Kemp, Haptic classification and recognition of objects using a tactile sensing forearm, in: Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems, 2012, pp. 4090–4097.
[76] S. Chitta, J. Sturm, M. Piccoli, W. Burgard, Tactile sensing for mobile manipulation, IEEE Transactions on Robotics 27 (2011) 558–568.
[77] F. Hammond, R. Kramer, Q. Wan, R. Howe, R. Wood, Soft tactile sensor array for micromanipulation, in: Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems, 2012, pp. 25–32.
[78] T. Field, Touch, MIT Press, 2001.
[79] L. Gartner, J. Hiatt, Color Textbook of Histology, Saunders, 2007.
[80] D. Purves, G.J. Augustine, D. Fitzpatrick, L.C. Katz, A.-S. LaMantia, J.O. McNamara, S.M. Williams, Neuroscience, Sunderland (MA), second ed., available: http://www.ncbi.nlm.nih.gov/books/NBK10895/, accessed 1 October 2013, 2001.
[81] R.S. Johansson, G. Westling, Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects, Exp. Brain Res. 56 (1984) 550–564.
[82] M. Richardson, The sense of touch: Touch sensation, Nurs. Times 104 (5) (2008) 29.
[83] P. Dario, C. Laschi, S. Micera, F. Vecchi, M. Zecca, A. Menciassi, B. Mazzolai, M. Carrozza, Biologically-inspired microfabricated force and position mechano-sensors, in: International Symposium on the Mechanics of Plants, Animals and their Environments, 2000.
[84] E. Weber, On the Tactile Senses, Academic Press, 1978.
[85] R. Johansson, Tactile sensibility in the human hand: receptive field characteristics of mechanoreceptive units in the glabrous skin area, J. Physiol. 281 (1978) 101–125.
[86] A. Vallbo, R. Johansson, Properties of cutaneous mechanoreceptors in the human hand related to touch sensation, Human Neurobiol. 3 (1984) 3–14.
[87] D. Katz, The World of Touch, L. Erlbaum Associates, 1989, translated to english by L.E. Krueger.
[88] R. Dahiya, L. Lorenzelli, G. Metta, M. Valle, POSFET devices based tactile sensing arrays, in: Proc. IEEE International Symposium on Circuits and Systems, 2010, pp. 893–896.
[89] P. Dougherty, Neuroscience Online, Ch. 4: Somatosensory Pathways, URL http://neuroscience.uth.tmc.edu/s2/, Accessed 1 October 2013, 1997.
[90] W. Penfield, T. Rasmussen, The Cerebral Cortex of Man: A Clinical Study of Localization of Function, Hafner, 1968.
[91] W. Schiff, E. Foulke, Tactual Perception: A Sourcebook, Cambrige University Press, 1982.
[92] M.A. Patestas, L.P. Gartner, A Textbook of Neuroanatomy, Blackwell Publishing, 2006, pp. 137–170. Chap. 10: The Ascending Sensory Pathways.
[93] M. Geerligs, Skin Layer Mechanics, Koninklijke Philips Electronics, 2009.
[94] A.C. Guyton, J.E. Hall, Guyton and Hall Textbook of Medical Physiology, Elsevier, 2011.
[95] P. O'Neil, K. Calhoun, Sensory deficits and behavioral deterioration in senescence, J. Abnormal Psychol. 84 (5) (1975) 579–582.
[96] J. Pattison, Effects of touch on self-exploration and the therapeutic relationship, J. Consult. Clin. Psychol. 40 (2) (1973) 170–175.
[97] J. Triplett, S. Arneson, The use of verbal and tactile comfort to alliviate distress in young hospitalized children, Res. Nurs. Health. 2 (1) (1979) 17–22.
[98] J. Jorgenson, Therapeutic use of companion animals in health care, J. Sch. Nurs. 29 (3) (1996) 249–254.
[99] T. Field, The importance of touch, Karger Gazette 67 (2004) 10–12.
[100] A. Crusco, C. Wetzal, The Midas touch: The effects of interpersonal touch on restaurant tipping, Personal. Soc. Psychol. Bull. 10 (4) (1984) 512–517.
[101] J. Fisher, M. Rytting, R. Heslin, Hands touch hands: Affective and evaluative effects of an interpersonal touch, Amer. Sociol. Assoc. 39 (4) (1976) 416–421.
[102] J. Burwell, May I touch you? Haptics in the multicultural workplace, Gend. J. (1999) 10.
[103] S. Thayer, Tactual Perception: A Sourcebook, Cambridge University Press, 1982, pp. 263–304. Chap. 8: Social Touch.
[104] R. Heslin, Steps toward a taxomony of touching, presented at the annual meeting of the Midwestern Psychological Association, Chicago, IL., 1974.
[105] R. Heslin, M. Patterson, Nonverbal Behavior and Social Psychology, Plenum Press, 1982.
[106] R. Heslin, T. Nguyen, M. Nguyen, Meaning of touch: the case of touch from a stranger or same sex person, J. Nonverbal Behav. 7 (3) (1983) 147–157.
[107] K.L. Johnson, R. Edwards, The effects of gender and type of romantic touch on perceptions of relational commitment, Nonverbal Behav. 15 (1) (1991) 43–55.
[108] D. Silvera Tawil, D. Rye, M. Velonaki, Interpretation of the modality of touch on an artificial arm covered with an EIT-based sensitive skin, Int. J. Robot. Res. 31 (13) (2012) 1627–1642.
[109] E. McDaniel, P. Andersen, International patterns of interpersonal tactile communication: a field of study, J. Nonverbal Behav. 22 (1) (1998) 59–75.
[110] S. Jones, The Right Touch: Understanding and Using the Language of Physical Contact, Hampton Press, 1994.
[111] S.M. Jourard, An exploratory study of body-accessibility, Br. J. Soc. Clin. Psychol. 5 (3) (1966) 221–231.
[112] S. Jones, E. Yarbrough, A naturalistic study of the meaning of touch, Commun. Monogr. 52 (1) (1985) 19–56.
[113] T. Nguyen, R. Heslin, M. Nguyen, The meanings of touch: Sex differences, J. Commun. 25 (3) (1975) 92–103.
[114] O. Zur, N. Nordmarken, To touch or not to touch: Exploring the myth of prohibition on touch in psychotherapy and counseling, Available: http://www.zurinstitute.com/touchintherapy.html, accessed 1 October 2013, 2010.
[115] M. Hunter, J. Struve, The Ethical Use of Touch in Psycotherapy, Sage Publications, 1998.
[116] A. Gallace, C. Spence, The science of interpersonal touch: an overview, Neurosci. Biobehav. Rev. 34 (2) (2010) 246–259.
[117] M. Hertenstein, D. Keltner, B. App, B. Bulleit, A. Jaskolka, Touch communicates distinct emotions, Emotion 6 (3) (2006) 528–533.
[118] M. Hertenstein, R. Holmes, M. McCullough, D. Keltner, The communication of emotion via touch, Emotion 9 (4) (2009) 566–573.
[119] D. Silvera-Tawil, D. Rye, M. Velonaki, Interpretation of social touch on an artificial arm covered with an EIT-based sensitive skin, Int. J. Soc. Robot. (2013). http://dx.doi.org/10.1007/s12369-013-0223-x.
[120] V. Lumelsky, M. Shur, S. Wagner, Sensitive skin, IEEE Sens. 1 (1) (2001) 41–51.
[121] T. Papakostas, J. Lima, M. Lowe, A large area force sensor for smart skin applications, in: Proc. IEEE Sensors, vol. 2, 2002, pp. 1620–1624.
[122] T. Someya, T. Sakurai, T. Sekitani, Large-area electronics based on organic transistors, in: Proc. IEEE Device Research Conference, 2006, pp. 209–210.
[123] W. Stiehl, C. Breazeal, Applying a "somatic alphabet" approach to inferring orientation, motion, and direction in clusters of force sensing resistors, in: Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems, vol. 3, 2004, pp. 3015–3020.
[124] T. Lomas, A. Tuantranont, A. Wisitsoraat, Polysilicon piezoresistive tactile sensor array fabricated by polyMUMPs process, in: Proc. IEEE Conference on Sensors, 2006, pp. 1313–1316.
[125] T. Mukai, M. Onishi, T. Odashima, S. Hirano, Z. Luo, Development of the tactile sensor system of a human-interactive robot "RI-MAN", IEEE Transactions on Robotics 24 (2) (2008) 505–512.

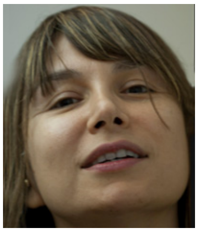
[126] J. Meyer, P. Lukowicz, G. Tröster, Textile pressure sensor for muscle activity and motion detection, in: Proc. IEEE International Symposium on Wearable Computers, 2006, pp. 69–72.
[127] G. Cannata, M. Maggiali, G. Metta, G. Sandini, An embedded artificial skin for humanoid robots, in: Proc. IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems, 2008, pp. 434–438.
[128] Y. Hasegawa, H. Sasaki, M. Shikida, K. Sato, K. Itoigawa, Magnetic actuation of a micro-diaphragm structure for an active tactile sensor, in: Proc. IEEE International Symposium on Micro-Nanomechatronics and Human Science and Symposium on Micro-Nanomechatronics for Information-Based Society, 2004, pp. 99–104.
[129] M. Goka, H. Nakamoto, S. Takenawa, A magnetic type tactile sensor by GMR elements and inductors, in: Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems, 2010, pp. 885–890.
[130] R. Reston, E. Kolesar, Pressure-sensitive field-effect transistor sensor array fabricated from a piezoelectric polyvinylidene fluoride film, in: Proc. Annual International Conference of the IEEE Engineering in Medicine and Biology Society, vol. 3, 1989, pp. 918–919.
[131] Y. Tanaka, M. Tanaka, S. Chonan, Development of a sensor system for measuring tactile sensation, in: Proc. IEEE Conference on Sensors, 2006, pp. 554–557.
[132] R. Dahiya, M. Valle, G. Metta, L. Lorenzelli, POSFET tactile sensor arrays, in: Proc. IEEE International Conference on Electronics, Circuits and Systems, 2007, pp. 1075–1078.
[133] H. Nicholls, Tactile sensing for robotics, in: Proc. IEE Colloquium on Robot Sensors, 1991, pp. 5/1–5/3.
[134] M. Ohka, H. Kobayashi, Y. Mitsuya, Sensing characteristics of an optical three-axis tactile sensor mounted on a multi-fingered robotic hand, in: Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems, 2005, pp. 493–498.
[135] Y. Ohmura, Y. Kuniyoshi, A. Nagakubo, Conformable and scalable tactile sensor skin for curved surfaces, in: Proc. IEEE International Conference on Robotics and Automation, 2006, pp. 1348–1353.
[136] J. Heo, C. Han, J. Lee, Evaluation of the tactile sensor element using the microbending optical fiber sensors, in: Proc. International Conference on Sensing Technology, 2007, pp. 74–78.
[137] B. Hutchings, A. Grahn, R. Petersen, Multiple-layer cross-field ultrasonic tactile sensor, in: Proc. IEEE International Conference on Robotics and Automation, vol. 3, 1994, pp. 2522–2528.
[138] W. Cho, K. Kim, K. Lee, Y. Kim, D. Lee, W. Kim, N. Cho, K. Park, H. Park, J. Park, B. Ju, Flexible tactile sensor fabricated using polymer membrane, in: Proc. IEEE Conference on Sensors, 2006, pp. 730–733.
[139] M.-Y. Cheng, W.-Y. Chang, L.-C. Tsao, S.-A. Yang, Y.-J. Yang, W.-P. Shih, F.-Y. Chang, S.-H. Chang, K.-C. Fan, Design and fabrication of an artificial skin using PI-copper films, in: Proc. IEEE International Conference on Micro Electro Mechanical Systems, 2007, pp. 389–392.
[140] T. Yoshikai, H. Fukushima, M. Hayashi, M. Inaba, Development of soft stretchable knit sensor for humanoids whole-body tactile sensibility, in: Proc. IEEE-RAS International Conference on Humanoid Robots, 2009, pp. 624–631.
[141] Y. Tanaka, K. Doumoto, A. Sano, H. Fujimoto, Development of a sensor system with syringe based on tactile sensing using balloon expansion, in: Proc. IEEE International Conference on Robotics and Automation, 2010, pp. 4861–4866.
[142] R. Russell, Robot Tactile Sensing, Prentice Hall, 1990.
[143] D. De Rossi, E. Scilingo, Skin-like sensor arrays, in: C. Grimes, E. Dickey, M. Pishko (Eds.), Encyclopedia of Sensors, American Scientific, 2006, pp. 535–556.
[144] M. Cutkosky, R. Howe, W. Provancher, Handbook of Robotics, Springer, 2008, pp. 455–476. Chap. 19: Force and Tactile Sensors.
[145] H. Hasegawa, Y. Mizoguchi, K. Tadakuma, A. Ming, M. Ishikawa, M. Shimojo, Development of intelligent robot hand using proximity contact and slip sensing, in: Proc. IEEE International Conference on Robotics and Automation, 2010, pp. 777–784.
[146] H. Iwata, S. Sugano, Human–robot-contact-state identification based on tactile recognition, IEEE Trans. Ind. Electron. 52 (6) (2005) 1468–1477.
[147] A. Schmid, N. Gorges, D. Goger, H. Worn, Opening a door with a humanoid robot using multi-sensory tactile feedback, in: Proc. IEEE International Conference on Robotics and Automation, 2008, pp. 285–291.
[148] G. Borghesan, G. Palli, C. Melchiorri, Friction compensation and virtual force sensing for robotic hands, in: Proc. IEEE International Conference on Robotics and Automation, 2011, pp. 4756–4761.
[149] M. Fumagalli, S. Ivaldi, M. Randazzo, L. Natale, G. Metta, G. Sandini, F. Nori, Force feedback exploiting tactile and proximal force/torque sensing, Auton. Robots 33 (2012) 381–398.
[150] A. Buchan, J. Bachrach, R. Fearing, Towards a minimal architecture for a printable, modular, and robust sensing skin, in: Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems, 2012, pp. 33–38.
[151] P. Mittendorfer, G. Cheng, Humanoid multimodal tactile-sensing modules, IEEE Transactions on Robotics 27 (3) (2011) 401–410.
[152] A. Schmitz, P. Maiolino, M. Maggiali, L. Natale, G. Cannata, G. Metta, Methods and technologies for the implementation of large-scale robot tactile sensors, IEEE Transactions on Robotics 27 (3) (2011) 389–400.
[153] P. Mittendorfer, G. Cheng, Open-loop self-calibration of articulated robots with artificial skins, in: Proc. IEEE International Conference on Robotics and Automation, 2012, pp. 4539–4545.
[154] P. Mittendorfer, G. Cheng, 3D surface reconstruction for robotic body parts with artificial skins, in: Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems, 2012, pp. 4505–4510.
[155] T. Minato, M. Shimada, S. Itakura, K. Lee, H. Ishiguro, Does gaze reveal the human likeness of an android?, in: Proc. IEEE International Conference on Development and Learning, 2005, pp. 106–111.
[156] M. Strohmayr, H. Wörn, G. Hirzinger, The DLR artificial skin, step I: Uniting sensitivity and collision tolerance, in: Proc. IEEE International Conference on Robotics and Automation, 2013, pp. 1004–1010.
[157] S. Youssefi, S. Denei, F. Mastrogiovanni, G. Cannata, A middleware for whole body skin-like tactile systems, in: Proc. Workshop on: Advances in Tactile Sensing and Touch based Human–Robot Interaction, 2012.
[158] N. Jamali, C. Sammut, Material classification by tactile sensing using surface textures, in: Proc. IEEE International Conference on Robotics and Automation, 2010, pp. 2336–2341.
[159] M. Cooney, S. Nishio, H. Ishiguro, Recognizing affection for a touch-based interaction with a humanoid robot, in: Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems, 2012, pp. 1420–1427.
[160] T. Mouri, H. Kawasaki, K. Yoshikawa, J. Takai, S. Ito, Anthropomorphic robot hand: Gifu hand III, in: Proc. International Conference on Computer Applications, 2002, pp. 1288–1293.
[161] M. Shimojo, A. Namiki, M. Ishikawa, R. Makino, K. Mabuchi, A tactile sensor sheet using pressure conductive rubber with electrical-wires stitched method, IEEE Sens. 4 (5) (2004) 589–596.
[162] J. Kim, W. Choi, H. Kwon, D. Kang, Development of tactile sensor with functions of contact force and thermal sensing for attachment to intelligent robot finger tip, in: Proc. IEEE Conference on Sensors, 2006, pp. 1468–1472.
[163] M. Strohmayr, H. Saal, A. Potdar, P. van der Smagt, The DLR touch sensor I: A flexible tactile sensor for robotic hands based on a crossed-wire approach, in: Proc. IEEE International Conference on Intelligent Robots and Systems, 2010, pp. 897–903.
[164] S. Teshigawara, T. Tsutsumi, S. Shimizu, Y. Suzuki, A. Ming, M. Ishikawa, M. Shimojo, Highly sensitive sensor for detection of initial slip and its application in a multi-fingered robot hand, in: Proc. IEEE International Conference on Robotics and Automation, 2011, pp. 1097–1102.
[165] F. Naya, J. Yamato, K. Shinozawa, Recognizing human touching behaviors using a haptic interface for a pet-robot, in: Proc. IEEE International Conference on Systems, Man, and Cybernetics, vol. 2, 1999, pp. 1030–1034.
[166] M. Maggiali, G. Cannata, P. Maiolino, G. Metta, M. Randazzo, G. Sandini, Embedded distributed capacitive tactile sensor, in: Mechatronics Forum Biennial International Conference, 2008.
[167] A. Schmitz, M. Maggiali, M. Randazzo, L. Natale, G. Metta, Prototype fingertip with high spatial resolution pressure sensing for the robot iCub, in: Proc. IEEE-RAS International Conference on Humanoid Robots, 2008, pp. 423–428.
[168] D. Hristu, N. Ferrier, R. Brockett, The performance of a deformable-membrane tactile sensor: Basic results on geometrically-defined tasks, in: Proc. IEEE International Conference on Robotics and Automation, vol. 1, 2000, pp. 508–513.
[169] K. Yamada, K. Goto, Y. Nakajima, N. Koshida, H. Shinoda, A sensor skin using wire-free tactile sensing elements based on optical connection, in: Proc. IEEE Annual Conference of the Society of Instrument and Control Engineers, vol. 1, 2002, pp. 131–134.
[170] Y. Yamada, M. Morizono, U. Umetani, T. Takahashi, Highly soft viscoelastic robot skin with a contact object-location-sensing capability, IEEE Trans. Ind. Electron. 52 (4) (2005) 960–968.
[171] J. Rossiter, T. Mukai, An LED-based tactile sensor for multi-sensing over large areas, in: Proc. IEEE Conference on Sensors, 2006, pp. 835–838.
[172] A. Ataollahi, P. Polygerinos, P. Puangmali, L. Seneviratne, K. Althoefer, Tactile sensor array using prismatic-tip optical fibers for dexterous robotic hands, in: Proc. IEEE International Conference on Intelligent Robots and Systems, 2010, pp. 910–915.
[173] A. Massaro, F. Spano, P. Cazzato, C. La Tegola, R. Cingolani, A. Athanassiou, Robot tactile sensing: Gold nanocomposites as highly sensitive real-time optical pressure sensors, IEEE Robot. Autom. Mag. 20 (2) (2012) 82–90.
[174] T. Salter, K. Dautenhahn, R. Boekhorst, Learning about natural human–robot interaction styles, Robot. Auton. Syst. 54 (2) (2006) 127–134.
[175] D. Rye, M. Velonaki, S. Williams, S. Scheding, Fish-bird: human–robot interaction in a contemporary arts setting, in: Proc. Australasian Conference on Robotics and Automation, 2005.
[176] R. Dahiya, M. Valle, G. Metta, L. Lorenzelli, A. Adami, Design and fabrication of POSFET devices for tactile sensing, in: Proc. IEEE Transducers, 2009, pp. 1881–1884.
[177] R. Dahiya, D. Adami, C. Collini, L. Barboni, M. Valle, L. Lorenzelli, R. Oboe, G. Metta, F. Brunetti, Towards tactile sensing system on chip for robotic applications, IEEE Sens. J. 11 (12) (2011) 3216–3226.
[178] B. Choi, S. Lee, H.R. Choi, S. Kang, Development of anthropomorphic robot hand with tactile sensor: SKKU hand II, in: Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems, 2006, pp. 3779–3784.
[179] T. Noda, T. Miyashita, H. Ishiguro, N. Hagita, Super-flexible skin sensors embedded on the whole body, self-organizing based on haptic interactions, in: Proc. Robotics: Science and Systems, 2008, pp. 294–301.
[180] Z. Hui, T. Ming, Y. Xi, L. Sheng, Pressure sensing fabric, in: MRS Proceedings, vol. 920, 2006.
[181] M.-A. Lacasse, V. Duchaine, C. Gosselin, Characterization of the electrical resistance of carbon-black-filled silicone: Application to a flexible and stretchable robot skin, in: Proc. IEEE International Conference on Robotics and Automation, 2010, pp. 4842–4848.

[182] T. Noda, T. Miyashita, H. Ishiguro, N. Hagita, Map acquisition and classification of haptic interaction using cross correlation between distributed tactile sensors on the whole body surface, in: Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems, 2007, pp. 1099–1105.
[183] T. Taichi, M. Takahiro, I. Hiroshi, H. Norihiro, Automatic categorization of haptic interactions—What are the typical haptic interactions between a human and a robot? in: Proc. IEEE-RAS International Conference on Humanoid Robots, 2006, pp. 490–496.
[184] R. Smith, B. Thomas, W. Piekarski, Tech Note: Digital Foam, Tech. Rep., Wearable Computer Laborator, University of South Australia, 2008.
[185] H. Alirezaei, A. Nagakubo, Y. Kuniyoshi, A tactile distribution sensor which enables stable measurement under high and dynamic stretch, in: Proc. IEEE Symposium on 3D User Interfaces, 2009, pp. 87–93.
[186] D. Silvera Tawil, D. Rye, M. Velonaki, Improved image reconstruction for an EIT-based sensitive skin with multiple internal electrodes, IEEE Trans. Robot. 27 (3) (2011) 425–435.
[187] R. Kramer, C. Majidi, R. Wood, Wearable tactile keypad with stretchable artificial skin, in: Proc. IEEE International Conference on Robotics and Automation, 2011, pp. 1103–1107.
[188] K. Noda, E. Iwase, K. Matsumoto, I. Shimoyama, Stretchable liquid tactile sensor for robot-joints, in: Proc. IEEE International Conference on Robotics and Automation, 2011, pp. 4212–4217.
[189] R. Tajima, S. Kagami, M. Inaba, H. Inoue, Development of soft and distributed tactile sensors and the application to a humanoid robot, Adv. Robot. 16 (4) (2002) 381–397.
[190] S. Lacour, J. Jones, S. Wagner, T. Li, Z. Suo, Stretchable interconnects for elastic electronic surfaces, Proc. IEEE 93 (8) (2005) 1459–1467.
[191] T. Loher, D. Manessis, R. Heinrich, B. Schmied, J. Vanfleteren, J. DeBaets, A. Ostmann, H. Reichl, Stretchable electronic systems, in: Proc. IEEE Electronics Packaging Technology Conference, 2006, pp. 271–276.
[192] M. Cheng, C. Tsao, Y. Yang, An anthropomorphic robotic skin using highly twistable tactile sensing array, in: Proc. IEEE Conference on Industrial Electronics and Applications, 2010, pp. 650–655.
[193] D. Lipomi, M. Vosgueritchian, B. Tee, S. Hellstrom, J. Lee, C. Fox, Z. Bao, Skin-like pressure and strain sensors based on transparent elastic films of carbon nanotubes, Nature Nanotechnol. 6 (2011) 788–792.
[194] J. Engel, J. Chen, Z. Fan, C. Liu, Polymer micromachined multimodal tactile sensors, Sensors Actuators A 117 (2005) 50–61.
[195] E. Hwang, Y. Kim, A polymer-based flexible tactile sensor and its application to robotics, in: Proc. IEEE Sensors, 2007, pp. 784–787.
[196] V. Ho, D. Dao, S. Sugiyama, S. Hirai, Design of a small-scale tactile sensor with three sensing points for using in robotic fingertips, in: Proc. IEEE International Conference on Robotics and Automation, 2010, pp. 4855–4860.
[197] H.-K. Lee, S.-I. Chang, E. Yoon, A flexible polymer tactile sensor: Fabrication and modular expandability for large area deployment, Microelectromech. Syst. 15 (6) (2006) 1681–1686.
[198] M. Nilsson, Tactile sensors and other distributed sensors with minimal wiring complexity, IEEE/ASME Trans. Mechatronics 5 (3) (2000) 253–257.
[199] L. Seminara, L. Pinna, M. Valle, L. Basiricò, A. Loi, P. Cosseddu, A. Bonfiglio, A. Ascia, M. Biso, A. Ansaldo, D. Ricci, G. Metta, Design, fabrication and test of arrays of piezoelectric transducers for robotic tactile sensors, in: Proc. Workshop on: Advances in Tactile Sensing and Touch based Human–Robot Interaction, 2012.
[200] D. Anghinolfi, G. Cannata, F. Mastrogiovanni, C. Nattero, M. Paolucci, Heuristic approaches for the optimal wiring in large scale robotic skin design, Comput. Oper. Res. 39 (2012) 2715–2724.
[201] Y. Kato, T. Mukai, T. Hayakawa, T. Shibata, Tactile sensor without wire and sensing element in the tactile region based on EIT method, in: Proc. IEEE Sensors, 2007, pp. 792–795.
[202] H. Alirezaei, A. Nagakubo, Y. Kuniyoshi, A highly stretchable tactile distribution sensor for smooth surfaced humanoids, in: Proc. IEEE Humanoids, 2007, pp. 167–173.
[203] A. Nagakubo, H. Alirezaei, Y. Kuniyoshi, A deformable and deformation sensitive tactile distribution sensor, in: Proc. IEEE International Conference on Robotics and Biomimetics, 2007, pp. 1301–1308.
[204] D. Silvera Tawil, D. Rye, M. Velonaki, Improved EIT drive patterns for a robotics sensitive skin, in: Proc. Australasian Conference on Robotics and Automation, 2009.
[205] H. Shinoda, H. Oasa, Passive wireless sensing element for sensitive skin, in: Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems, vol. 2, 2000, pp. 1516–1521.
[206] M. Hakozaki, H. Shinoda, Digital tactile sensing elements communicating through conductive skin layers, in: Proc. IEEE International Conference on Robotics and Automation, vol. 4, 2002, pp. 3813–3817.
[207] H. Shinoda, H. Chigusa, Y. Makino, Flexible tactile sensor skin using wireless sensor elements coupled with 2D microwaves, J. Robot. Mechatronics 22 (6) (2010) 748–785.
[208] B. Browatzki, V. Tikhanoff, G. Metta, H. Bülthoff, C. Wallraven, Active object recognition on a humanoid robot, in: Proc. IEEE International Conference on Robotics and Automation, 2012, pp. 2021–2028.
[209] S. Koo, J.G. Lim, D. Kwon, Online touch behavior recognition of hard-cover robot using temporal decision tree classifier, in: Proc. IEEE International Symposium on Robot and Human Interactive Communication, 2008, pp. 425–429.
[210] H. Knight, R. Toscano, W. Stiehl, A. Chang, Y. Wang, C. Breazeal, Real-time social touch gesture recognition for sensate robots, in: Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems, 2009, pp. 3715–3720.
[211] G. Cannata, S. Denei, F. Mastrogiovanni, Towards automated self-calibration of robot skin, in: Proc. IEEE International Conference on Robotics and Automation, 2010, pp. 4849–4854.
[212] A. Del Prete, S. Denei, L. Natale, F. Mastrogiovanni, F. Nori, G. Cannata, G. Metta, Skin spatial calibration using force/torque measurements, in: IEEE/RSJ International Conference on Intelligent Robots and Systems, 2012, pp. 3694–3700.
[213] T. Hoshi, H. Shinoda, 3D Shape measuring sheet utilizing gravitational and geomagnetic fields, in: Proc. Annual Conference of the Society of Instrument and Control, 2008, pp. 915–920.
[214] T. Shibata, T. Mitsui, K. Wada, A. Touda, T. Kumasaka, K. Tagami, K. Tanie, Mental commit robot and its application to therapy of children, in: Proc. IEEE International Conference on Advanced Intelligent Mechatronics, vol. 2, 2001, pp. 1053–1058.
[215] T. Kanda, T. Hirano, D. Eaton, H. Ishiguro, Interactive robots as social partners and peer tutors for children: a field trial, Hum.-Comput. Interact. 19 (2004) 61–84.
[216] D. Silvera Tawil, D. Rye, M. Velonaki, Touch modality interpretation for an EIT-based sensitive skin, in: Proc. IEEE International Conference on Robotics and Automation, 2011, pp. 3770–3776.
[217] H. Iwata, S. Sugano, A system design for tactile recognition of human–robot contact state, in: Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems, vol. 1, 2003, pp. 7–12.
[218] M. Black, Y. Yacoob, Tracking and recognizing rigid and non-rigid facial motions using local parametric models of image motion, in: Proc. International Conference on Computer Vision, 1995, pp. 374–381.
[219] A. Fridlund, The Psychology of Facial Expression, Cambridge University Press, 1997, pp. 103–129. Chap. 5: The New Ethology of Human Facial Expressions.
[220] T.L. Nwe, F.S. Wei, L. De Silva, Speech based emotion classification, in: Proc. IEEE Region 10 International Conference on Electrical and Electronic Technology, vol. 1, 2001, pp. 297–301.
[221] C. Busso, Z. Deng, S. Yildirim, M. Bulut, C.M. Lee, A. Kazemzadeh, S. Lee, U. Neumann, S. Narayanan, Analysis of emotion recognition using facial expressions, speech and multimodal information, in: Proc. International Conference on Multimodal Interfaces, 2004, pp. 205–211.
[222] C. Liu, P. Rani, N. Sarkar, An empirical study of machine learning techniques for affect recognition in human–robot interaction, in: Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems, 2005, pp. 2662–2667.
[223] K. Gouizi, F. Reguig, C. Maaoui, Analysis physiological signals for emotion recognition, in: Proc. IEEE International Workshop on Systems, Signal Processing and their Applications, 2011, pp. 147–150.
[224] B. Schuller, M. Lang, G. Rigoll, Multimodal emotion recognition in audiovisual communication, in: Proc. IEEE International Conference on Multimedia and Expo, vol. 1, 2002, pp. 745–748.
[225] J. Kelley, An iterative design methodology for user-friendly natural language office information applications, ACM Trans. Off. Inf. Syst. 2 (1984) 26–41.
[226] S. Yohanan, K. MacLean, Design and assessment of the haptic creature's affect display, in: Proc. ACM/IEEE International Conference on Human–Robot Interaction, 2011, pp. 473–480.
[227] J. Russell, A circumplex model of affect, J. Personal. Soc. Psychol. 39 (6) (1980) 1161–1178.

David Silvera-Tawil was born in Mexico City where he obtained his BE (1st Class) in Electronics and Telecommunications at the Universidad Iberoamericana (2002). He received a MEngStud (Hons) in Mechatronics (2007) and a Ph.D. in Artificial Skin and Human–Robot Interaction (2012) from The University of Sydney. He is currently a Postdoctoral fellow at the Creative Robotics Lab, The University of New South Wales. His long-term research interests are in the area of human–robot interaction, social robotics and assistive robotics. He aims for humans and robots to share the same physical space, interacting and communicating in similar, intuitive ways and working, helping and cooperating as peers to achieve both shared and independent goals. His current research contributes towards expanding the understanding of human behaviour in social environments and improving social and affective human–robot interaction. His previous research involved interactive interfaces, remote laboratories for distance learning, artificial robotic 'skin' and touch interpretation in human–robot interaction.

David Rye works in embedded and applied control of machinery, and in the design and implementation of computer-controlled systems. Although his background is originally in Mechanical Engineering, he now works principally on computerised machinery, electronics, software and systems design. He has conducted industrial research and development projects related to automation and control of machinery, including shipboard and container-handling cranes and the system design and experimental validation of autonomous vehicles. Since 2003 he has worked on human–robot interaction in a media arts context. In 2006 he co-founded, with Mari Velonaki, the Centre for Social Robotics within the Australian Centre for Field Robotics at the University of Sydney. He is also

internationally recognised as a pioneer in the introduction and development of university teaching in Mechatronics, having instituted the first Australian Bachelor of Engineering in Mechatronics in 1990.



Mari Velonaki has worked as a Researcher and Artist in the field of interactive media art since 1997, driven by her fascination with the complex area of human–machine interaction. Her research begins from a series of interactive installations that engage the spectator/participant with digital and robotic characters in interplays stimulated by sensory triggered interfaces. Her principal contribution to the field of HRI is the creation of experimental interfaces that allow for the development of haptic and immersive relationships between the participants and the robotic agents. She has created intellectually and emotionally engaging human–machine interfaces that incorporate movement, speech, touch, breath, electrostatic charge, artificial vision, light and text.

In 2003 she began to work with robotics, initiating and leading a major Australian Research Council Linkage art/science research project 'Fish–Bird: Autonomous Interactions in a Contemporary Arts Setting' (2004–2006) in collaboration with robotics scientists at the Australian Centre for Field Robotics. 'Fish–Bird' is recognised internationally as a significant artwork and as an exemplary model of fully-engaged interdisciplinary research.

She has actively advocated the need for a dedicated research space for Social Robotics in Australia. In 2006 she co-founded, with Associate Professor Rye, the Centre for Social Robotics; a centre dedicated to cross-disciplinary research into human–robot interaction in environments that incorporate the general public. In 2007 she was awarded an Australia Council for the Arts Visual Arts Fellowship and in 2009 she was awarded an ARC Discovery Grant 'Physicality, tactility, intimacy: interaction between humans and robots' (2009–2013) and a Queen Elizabeth II Fellowship. She is currently working on applying sensing technology to the humanoid robot 'Diamandini' which is one of the outcomes of this project.

She is the Director of the recently established Creative Robotics Lab, at the National Institute of Experimental Arts, COFA at the University of New South Wales. Her interactive installations have been exhibited in major museums worldwide.