ORIGINAL RESEARCH

FACE: facial automaton for conveying emotions

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Abstract: The human face is the main organ of expression, capable of transmitting emotions that are almost instantly recognised by fellow beings. In this paper, we describe the development of a lifelike facial display based on the principles of biomimetic engineering. A number of paradigms that can be used for developing believable emotional displays, borrowing from elements of anthropomorphic mechanics and control, and materials science, are outlined. These are used to lay down the technological and philosophical premises necessary to construct a man–machine interface for expressing emotions through a biomimetic mechanical head. Applications in therapy to enhance social skills and understanding emotion in people with autism are discussed.

Keywords: facial automaton, man–machine interface, biomimetics, electroactive polymers, autism

Introduction

In recent years, the nonverbal expression of emotional states has rapidly become an area of interest in computer science and robotics. These developments parallel with important streams of thought in other fields, such as the neurosciences, cognitive science, biology, developmental psychology and ethology. A great deal of research has been carried out in applications such as robotics and human–computer interaction (HCI), where the power of facial emotional expressions in human–human and human–machine communication has been recognised. Several systems capable of automatic analysis, interpretation and categorisation of basic human facial expressions have been developed (Ekman 1989; Terzopoulos and Waters 1993; Essa 1995).

The other side of HCI involves the generation of emotion and expression in artificial systems. These can be divided into software-based systems and real three-dimensional (3D) artifacts, otherwise known as biologically inspired robots or sociable agents. Most emphasis has been given to the former; in fact many robotics researchers are investigating the emulation of human expression on computer-generated images. Very little has been obtained towards the realisation of a 3D expressive face. Nevertheless, pioneering research work on the subject of sociable agents is being carried out at Massachusetts Institute of Technology (MIT) by Breazeal and Scassellati (2000). They have designed a robot, known as KISMET, to interact socially with human 'parents'. It integrates perception, attention, 'drives', basic 'emotions', behaviour selection and motor action. In this architecture, the biomimetic aspects of emotional expression are not in the foreground and are at present reduced to meaningful but cartoon-like elements. A different – but nonetheless interesting – approach to the creation of agents emotionally and socially meaningful to humans is research aimed at endowing robots with more naturalistic mimic expressions, exploiting structures and actuators that can more closely replicate the subtleties of human movement. At the Science University of Tokyo, an android face with an elastomer skin overlying the mechanical skull produces a range of expressions using strategically positioned shape memory alloy actuators. The elastomer skin is shaped, tinted and made up to resemble the face of a woman; however, a smile takes a rather long time to fade because of the long relaxation times of the alloys (Hara et al 1998). For the moment, the applications of these research-oriented systems are limited to exploring social behaviour and emotion in man-made systems, with the ultimate aim of 'improving man–machine interfaces'.

Facial androids abound in the entertainment industry (Willis 2003) and have now achieved a high degree of believability, at least on celluloid. These systems have a remarkable aesthetic quality when they have been adequately retouched by lighting and graphic artists and are actuated by slow-moving motors and cables attached to an inert silicone skin. Seen in real life they are about as believable as a mannequin.

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In summary, although some researchers and many artists are investigating the emulation of human expression and the replication of its aesthetic qualities, little attempt has been made towards the realisation of a 3D expressive face with truly lifelike or believable qualities.

For the past 5 years, we at the University of Pisa have been involved in an ambitious project to develop a believable facial display system based on biomimetic engineering principles. The system is called FACE: facial automaton for conveying emotions (Figure 1). The underlying philosophy and design approach of the display is founded on the simulation of biological behaviour using materials, structures and control algorithms that can replicate some of the functions and responses of living systems. The long-term aim of the project is far reaching and culminates in achieving true believability, visually as well as in terms of texture and motion, in synthetic structures with human-like forms. At present, the immediate objective is focused upon simulating emotion in a 3D lifelike display and exploring its use in social skills and emotional therapy in individuals with autism.

FACE: the facial automaton

The aim of the FACE project is to realise a mechanical clone of a human head. The architecture of the facial automaton can be divided into three main sections (see Figure 2): an anthropomorphic head (AH), an anthropomorphic control (AC) system and an artificial decision unit (ADU).

The anthropomorphic head

To obtain an artificial AH that embodies passive facial muscular and skeletal (skull) structures we start from a real

Figure 1 Three different phases of the development of FACE (facial automaton for conveying emotions).

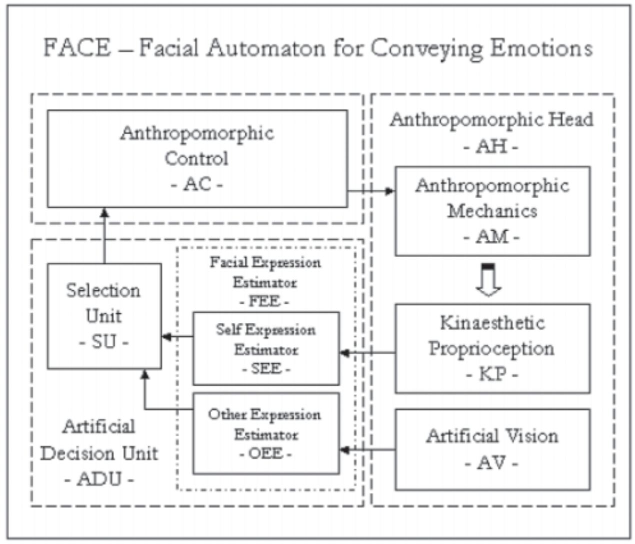

Figure 2 The architecture of FACE.

subject and then attempt to reconstruct the hard and soft tissues. A copy of the skull is obtained starting from CAT (computerised axial tomography) data and by means of appropriate software of volumetric virtual reconstruction (MIMICS 2003). A 'segmentation' process to isolate the skull is applied on the data, and the skull can be physically reconstructed in resin by means of CAD/CAM techniques. Reconstruction of soft tissues, on the other hand, is more difficult. In fact, were we to use a similar process, nuclear magnet resonance (NMR) is necessary. Starting from these data, each muscle has to be *segmented* and reconstructed; it is a long and complex process because of the difficulties of isolating muscles from images. For this reason, we have adopted a methodology known in the field of anthropology as facial reconstruction (Prag and Neave 1997). The technique involves the manual reconstruction of the facial muscular structure on the basis of tables indicating the thickness of soft tissues in different fixed points of the skull. The main facial muscles were separately reconstructed by using soft materials. This architecture was then coated by an artificial skin.

The artificial skin of FACE, which is a thin silicone-based mask equipped with a distributed kinaesthetic proprioception (KP) system, coats the AH. It is fabricated by means of life-casting techniques and aesthetically represents a copy of the skin of the subject, both in shape and texture. Prosthetic-grade alginate, plaster and plaster bandages are used to make casts of exceptional quality. Once the life cast is realised, it is covered with mouldable silicone rubber. This allows a silicone-based mould of a model's face to be obtained. The silicone-based mould is supported by applying plaster around it. To mimic the supple flexibility of human skin, the mask of FACE is cast by filling the mould with a liquid silicone elastomer, which, once hardened, resembles the natural viscoelasticity of human tissue. Liquid silicone is mixed with pigments to emulate a medium level of melanin and to reproduce different shades on the face. An artificial muscle architecture is inserted into the passive muscular structure within the AH. In particular, the artificial muscle architecture, which we call the 'anthropomorphic mechanics' (AM), is connected between the skin and the skull (Figure 2).

Social nonverbal communication is largely dependent on the ability of the eyes to express emotions and track subjects. These actions are performed by the complex eyeball muscle system. An important feature of the AH is the artificial eyeballs and eyelids, which replicate the eye colours and shape of the selected subject. A system consisting of linear actuators made of dielectric elastomers designed to mimic the architecture of the human eye is under development. In particular, actuators are connected to its eyeballs and are aimed at reproducing actions exerted by the eyelids and by the four main muscles of the human eyeball: the superior rectus, inferior rectus, lateral rectus and medial rectus.

The anthropomorphic control

Humans can easily express a mime and communicate their feelings and emotions. These tasks are extremely complex for a biomimetic android head, just as body movements are complex for a biomimetic robot. Due to the high dimensionality of the configuration space and redundancy of the system, such devices are very hard objects from the control point of view. It is evident that the process of 'rationalisation and simplification' in the design of artificial moving parts leads to the choice of the smallest possible number of controls. For this reason, most research on humanoid control draws inspiration and models from biology, in particular from neuroscience of motor control and coordination (Brooks et al 1999; Schaal 1999; Giszter et al 2000; Sarkar et al 2001). The biological paradigm is completely different in the sense that the number of muscles and tendons is much higher than the actual degrees of freedom of, for instance, a limb. Indeed, in human beings, routine tasks are carried out by an almost subconscious involuntary control, since we make use of sensory motor maps that have already been learned. Were we to reprogram these maps each time we perform a task, it would be a lot more difficult to learn complex motor actions. In accordance with this biological paradigm, a class of nonlinear controls along the lines of Feldman's (1979, 1986) model for muscle control has been developed (De Rossi, Di Puccio et al 2002; Lorussi et al 2003). Although this approach diverges from the framework of classic control theory, it may lead to motion that is more 'believable' than that of a traditional robotic limb. This type of control scheme will be implemented in FACE.

The artificial decision unit

The ADU includes a 'facial expression estimator' (FEE) system based on an artificial vision device and a 'selection unit' (SU) based on imitation paradigms. The use of imitation is fundamental for a biomimetic and behaviour-based approach to humanoid control and learning. Imitation involves the classification of visual input for recognition of human behaviour and allows the actuating control system to perform general movements and imitation learning. The ADU communicates with the AC and manages the expressivity of FACE. The SU is based on a neural network system and makes decisions based on previous learning experiences to generate the output desired to bestow FACE with its final expression. The FEE is divided into two sections: a 'self expression estimator' (SEE) and an 'other expression estimator' (OEE). The OEE receives its input by means of an 'artificial vision' (AV) device already developed, which provides FACE with the ability to recognise a number of expressions. The device includes an attention system and a model for facial expression recognition. The SEE, on the other hand, is based on the processing of data obtained from the sensorised artificial skin, as described in the next section.

Recently, automatic face recognition by means of computer vision has become a popular application field, resulting in commercial products such as FaceIt®, designed at the Computational Neuroscience Laboratory at Rockefeller University (FaceIt 2003). Nevertheless, the problem of automatic recognition of facial expressions still remains a challenging topic of application-oriented research work (Lien 1998).

Ekman's studies to construct a system for the detailed description of emotional expressions, the 'facial action coding system' (FACS), were important sources used by computer science and robotic researchers to explore the field of emotional expression and communication (Ekman and

Rosenberg 1997). FACS measures the movements of forty muscles in the face, classifying them as 'action units' (AUs). One AU represents a movement that a group of muscles make to obtain a particular expression. Thus, a facial expression can be captured by an artificial vision system, or simply a camera, and by means of a suitable algorithm, divided into its component AUs and subsequently identified by FACS coding.

Terzopoulos and Waters (1993) have developed techniques for facial expression recognition; in particular, a model of the skin and facial muscles based on FACS. Images acquired by the artificial vision system are converted into 2D potential functions whose local minima correspond to salient facial features (snakes). The snakes are tracked through each image at each time step. With the aim of representing muscle actions that lead to a skin deformation that matches with the image analysed, a 3D model of the face is deformed to approximate the AUs involved. By using this procedure, a facial expression can be identified.

Our approach uses a different technique; it is based on the AV system, realised using a CCD camera and a fringe pattern analysis (Kozlowski and Serra 1999). A curvature map and a 3D mesh of the head of a subject are calculated from images acquired with the camera. A dedicated process detects a number of points (markers), which are used to divide the human face into main zones (ie eyes, front, nose, mouth and chin). Data of each area are processed by a hierarchical neural-network architecture based on self-organising maps (SOMs) and error backpropagation (EBP). An output classifier is used to classify the facial expression of the subject. Figure 3 shows a block scheme of the system.

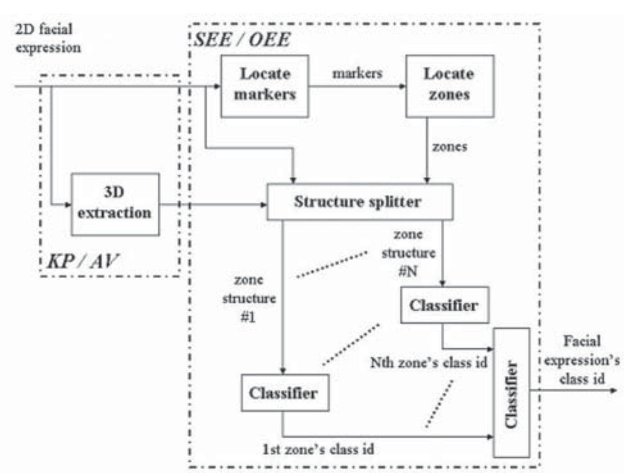

Figure 3 The 'other expression estimator'.

Kinaesthetic proprioception: biomimetic facial skin as a redundant self-sensory apparel for the system

The skin not only bestows expressivity and appearance but also sensing. Sensors in the skin are widely distributed and provide both tactile and kinaesthetic information. In an artificial sensing skin, the role of distributed sensors should not be to give an extremely accurate individual position of each element constituting FACE, but to enable a representation of the overall shape taken by the display. The skin of FACE is a complex 2D polymeric structure, and its response to simultaneous deformations in different directions is not easily reduced to a mathematical description. Thus, in this context, our biomimetic design is based on providing the artificial skin with a sort of proprioceptive mapping to approach the final required expression by a process of supervised learning. The supervised learning protocol leads FACE through a trial-and-error procedure until the system converges to a desired expression. Without sensing, the control of facial expression is open loop and hence unacceptable.

The artificial silicone skin of FACE is deformable, so the sensors have to be deformable too. Problems relating to the monitoring of the kinematics of the human body have been widely studied (De Rossi et al 1999), and devices able to detect body movements by means of wearable distributed sensing fabrics have been developed (De Rossi et al 2003). For the realisation of a poroelastic biomimetic skin with embedded sensing fibres, two types of piezoresistive weavable fibres are being developed. The first, filled rubber-coated threads (carbon-filled rubbers, CFR), which are sensitive to slowly varying deformations can, for example, map the 'steady-state' expression or the mood (Scilingo et al 2004). In contrast, conducting polymer fibres form the second class and are capable of mapping rapidly changing movements corresponding to immediate expressions deriving, for instance, from temper. Polypyrrole (PPy), a π-electron conjugated conducting polymer, which combines good properties of elasticity with mechanical and thermal transduction, is particularly suitable for this application. PPy-coated Lycra® fabrics have been prepared using the method reported by De Rossi et al (1999). Sensors based on CFR are realised either by directly printing the carbon/rubber mixture onto fabrics or by weaving CFR-coated fibres.

The sensors have been characterised in terms of their quasi-static and dynamic electromechanical transduction properties, and the thermal and ageing properties of the sensing fabrics have also been assessed (De Rossi, Carpi et al 2002).

From a technical viewpoint, a piezoresistive woven sensing fabric is a tissue whose local resistivity is a function of the local strain. In a discrete way, it can be thought of as a 2D resistive network where single resistors have a nonlinear characteristic that depends on the local strain. To know the exact deformation of the artificial skin, the resistance of every resistor, ie of every single tissue element, could be measured. However, this would place too much importance on the behaviour of each resistor and would require an exceedingly large number of electrical paths to be taken out of the system. It would also mean forcing the system into the common mental scheme of the Euclidean spatial representation of objects, which may not be the most convenient in this context.

For these reasons, we measure the impedance only between points located at the borders of the tissue. The integral impedance pattern, then, is a function of the overall shape of the tissue and allows mapping between the 'electrical space' and the 'expression space'. This method is in line with current thinking on perception and action (Berthoz 1997) and enables fast correction of the expression space according to the proprioceptive mapping pattern provided by the distributed sensing fabric. A similar procedure has been applied to the problem of recognising the position of an arm from a set of electrical signals originating from tissue sensors positioned on a shoulder joint, with excellent results (De Rossi, Carpi et al 2002).

Structures that could be implemented by means of this technology are numerous. In the case of FACE, we have developed a sensorised matrix (Figure 4), which has been integrated into the silicone-based mask. The matrix resistance can be read from its boundaries. In Figure 4a, the lines are the sensors, which are all connected with each other. Data can be generated by multiplexing the injection of a current in the different lines. This produces different voltages across the lines as a consequence of a deformation; the voltages are acquired and processed by a dedicated electronic device.

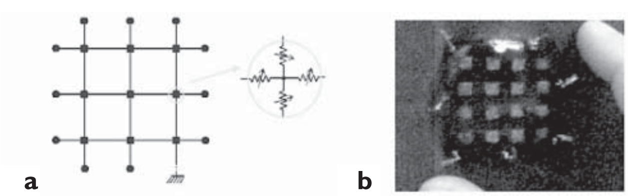

Figure 4 Scheme (a) and photo (b) of the sensorised matrix.

A liquid-filled cellular matrix, like human skin, is easily elongated, whereas elastomers require considerably greater force. This means that powerful and thus large actuators are required, or the skin architecture needs to be modified. Several methods for such modifications are available. The first employs liquid- or air-filled pouches in the skin, but this is complicated and costly. The second method involves the strategic reduction of skin thickness. The latter technique has been adopted for FACE. Once poured, the silicone can be modelled so as to obtain different thicknesses of skin. The nose and the boundaries of the face can be made thicker so as to fix the skin to the skull in those regions. The resulting variable skin thickness enables more lifelike dynamics of the skin, more closely resembling natural facial expressions.

Should silicone not respond in an appropriately dynamic manner, we will examine the feasibility of using poroelastic hydrogels with embedded pre-stressed sensing fibres to realise the dermal layer of FACE.

Human muscles and artificial actuators: borrowing from anthropomorphic mechanics

In the human face, more than 55 000 different facial expressions can be generated by more than 200 voluntary muscles (Duchenne de Boulogne 1990; Terzopoulos and Waters 1993). These numbers give a rough idea of the extreme complexity, from an engineering point of view, of the mechanical system represented by the human face. A further complication, which defies any attempt at analysis, modelling and reproduction of such a system, is introduced by the intrinsic nonlinearities of the biological materials and controls underlying its mechanical functioning. In fact, muscles consist of bundles of contracting fibres, which pull nonlinear facial soft tissue (Figure 5) to which they are bounded, and are driven by a nonlinear control, similar to that described by Feldman (1979, 1986).

Furthermore, the number of facial muscles is much higher than the actual degrees of freedom, and while, generally, in the rest of the body the primary muscle associated with a particular action is easily identified, the complexity of facial expressiveness implies that more than one muscle generally performs a given action. Therefore, it

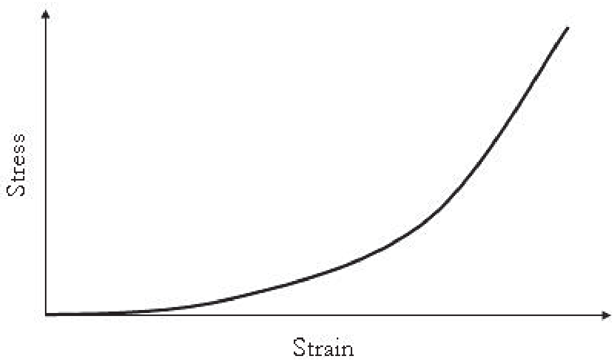

Figure 5 Typical stress–strain curve of the facial soft tissue.

is the concerted action of several muscle contractions that ultimately gives rise to a particular expression. The physical consistency of skin as well as the synergy between it and facial muscles provide the appearance that we are used to and trained to 'believe' and that is so meaningful to us at both the conscious and unconscious levels. This aspect is of great importance in a static face and more so where dynamic behaviour is concerned.

Biomimetic actuation using Feldman's muscle model

The actuation of a believable and anthropomorphic facial automaton involves the solution of problems having a level of complexity comparable to that of the biomechanical architecture of the human face. In fact, considering the viscoelastic behaviour of the silicone skin of FACE, believable anthropomorphic control of the actuators employed to move the skin is a challenging task requiring significant technological and engineering breakthroughs.

In the context of actuation, believability is the ability of the system to produce recognisable expressions through movements similar to those exerted by biological muscles. This means that each point of the skin should not only move to a given position by the action of a definite force, but should do so with the fluidity and grace of biological systems. This level of performance could be obtained by means of artificial actuating devices with control of their geometrical status as well as of their stiffness so as to mimic biological muscles. In fact, the variable slope of the mechanical force-length characteristic of a muscle allows humans to modulate their interactions with their surrounding environment more or less 'softly' in relation to the intrinsically variable compliance of their muscular system.

Many of the features of muscular contraction can be described by Feldman's model. In this model, a muscle's contracting force (F_m) depends on its intrinsic pseudo-stiffness (k), its effective length (x) and its rest length (λ) as follows:

$$F_m = k(x-\lambda)^2 u(x-\lambda)$$

where $u(x-\lambda)$ is the Heaviside function. Agonist and antagonist muscles can be grouped together, and position and stiffness of a pair or more of muscles can be controlled through modulation of muscle rest lengths.

A device force-length characteristic similar to that described by Feldman would allow the desired control of the system stiffness. In this regard, a methodology of control of such an actuating device aimed at reproducing the mechanical behaviour of human muscles was theoretically developed (De Rossi, Di Puccio et al 2002; Lorussi et al 2003). This biomimetic control is based on a functional structure and a driving strategy of the device inspired by those adopted in biological systems. The Feldman muscle is made up of a set of active elements (motor units) with different rest lengths. These units are activated by a progressive recruitment, whereby the quadratic characteristic of the entire muscle is due to the super-imposition of those of the elementary units. Following this concept, a bundle of artificial active fibres was considered as the actuating macro-device, and a suitable algorithm was developed to calculate values of a definite set of fibre parameters necessary to reproduce the characteristics of Feldman-type muscle. The algorithm is valid for fibres assumed to be able to elongate or contract in response to an electrical stimulus regardless of their physical constitution (Lorussi et al 2003). This type of control algorithm could enable the expression of FACE to be much more human-like than those used in traditional robotic control.

Materials for actuation

One of the most challenging tasks in the development of FACE is the realisation of high-performance actuators. They should enable actuation of an artificial skin and possess static and dynamic characteristics similar to those of human muscles to attain a satisfactory degree of 'believability'. Many efforts are presently focused on the realisation of pseudo-muscular actuators showing performances similar to those of natural muscles, such as built-in tuneable compliance, large strains, high active stresses (0.1–0.5 MPa), high efficiency, low volume/power ratio ($< 10^{-8}$ m^3/W) and fast response times (eg the average shortening speed of an unloaded sarcomere is about 5 μm/s).

Traditional and consolidated actuating technologies consent the achievement of only few of these characteristics, and, for several years, attention has been focused on polymer devices. In particular, we believe dielectric elastomers, which have gained growing interest during the last few years, are promising superior actuating materials for use in FACE. When a thin film of an insulating rubber-like material is sandwiched between two compliant electrodes, and a voltage difference is applied between them, the polymer undergoes an electric field-sustained deformation, which is mainly due to the electrostatic forces exerted by the electrode-free charges (Pelrine et al 1998, 2000). The resulting strain is proportional to the square of the applied electric field. Dielectric elastomers possess excellent figures of merit: linear actuation strains of up to 60%, fast response time (down to tens of milliseconds) and they generate stresses of the order of megapascals. The price for achieving these high-level performances is the very high driving electric field needed (order of 100 V/μm) (Pelrine et al 2000; Carpi et al 2003; Carpi and De Rossi 2004). Many actuating configurations made of dielectric elastomers have been proposed, including planar, tube, roll, diaphragm and bender (Pelrine et al 1998, 2000; Pei et al 2003).

Linear actuators showing electrically activated contractions or, alternatively, elongations, can be advantageously used, for the actuation of the skin of FACE, within an agonist–antagonist couple. Such devices are useful for the emulation of the resulting functionalities of fusiform muscles as well as sphincter muscles. For example, a linear compliant device can be easily looped to confer it sphincter-like capabilities owing to its internal state of stress.

A new configuration for a linear actuator, which is expected to be able to sustain contractions in response to an electrical stimulus (as for muscles), is currently under development. It consists of a dielectric elastomer having a structure twisted along its central axis, which has to be completed by the integration of two compliant electrodes having the same shape (Carpi and De Rossi 2003).

Finally, novel engineering approaches could be successfully used to simulate sheet muscles. Such muscles cannot be represented by a dielectric elastomer actuator having a simple planar configuration, which would be able only to actively elongate in the planar direction, instead of contract as required. The microfabrication of morphologically bionspired actuating configurations may allow the realisation of actuators similar to facial sheet muscles (such as the frontalis muscle).

Once realised and tested, dielectric elastomer actuators, which are most suited for application in FACE, will be embedded in the passive silicone architecture of the AH with particular attention to their size and placement.

Discussion: applications in therapy for autism

In FACE, the therapeutic approach stems from the cognitive theory of mindblindness (Baron-Cohen 1997), which can explain some of the social and communication problems of autistic people. It is well established that a core difficulty for people with autism spectrum conditions is in the area of recognising emotions and mental states. This is thought to underlie the social difficulties that people with autism spectrum conditions show.

Mindblindness suggests that autistic individuals have difficulty in conceiving of people as mental agents; that is, individuals with different knowledge, emotions, thoughts and perspectives. Mindblindness is thus the inability to perceive another person's mental state. Abnormalities in understanding other minds is not the only psychological feature of autistic spectrum conditions, but it seems to be a core, and possibly universal, abnormality among such individuals. An autistic person's social intelligence lags behind his or her non-social intelligence, and varying degrees of mindblindness – ranging from severe through to moderate, or even just very mild – are present in the spectrum. Recent studies have shown, however, that individuals, particularly those with high functioning autism, can learn to cope with common social situations if they are made to enact possible scenarios they may encounter. By recalling appropriate modes of behaviour and expressions in specific situations, they are able to react appropriately. There are now a number of highly structured therapeutic approaches based on emotion recognition and social skill training using photographs, drawings, videos or DVD-ROMs (for example, Mind Reading, produced by Human Emotions, UK). Their aim is to enable autistic individuals to interpret meanings and intentions of people and to anticipate their emotional reactions to typical situations they may encounter during the course of their daily lives. Previous work shows that basic emotion understanding can be taught, though generalisability remains a problem.

FACE

The 3D display described here will have greater visual impact for people with autism or Asperger's syndrome and can greatly reinforce this training method. It will also enable more complex and varied situations to be constructed during therapy. Our initial objective is to evaluate the therapeutic effect of FACE on patients with high functioning autism as regards to emotion recognition and compare the results with traditional training methods. At present, FACE is capable of generating the 7 basic expressions as classified by Ekman (1989): neutrality, happiness, surprise, anger, disgust, sadness and fear.

Currently, the only robotic system for therapeutic purposes is the AURORA (autonomous robotic platform as a remedial tool for children with autism) project, which uses a mobile robot to encourage children with autism to take initiative and use the robotic 'toy' to become engaged in a variety of different actions (Dautenhahn et al 2002). This approach is different from that described here, not only on the basis of the theoretical psychology underlying its development, but also because the robots used in the AURORA project are generally boxes with wheels, incapable of any biomimetic or emotional representation, or expressionless dolls (Robins et al 2004). Although the full potential of robots in therapy and education of children with autism has yet to be revealed, the initial results from this project demonstrate that children with autism can interact proactively with robots and often end up using them as mediators for interactions with other humans. Thus, their predilection for interaction with non-human artifacts can be exploited in a positive manner through the use of humanoid and non-humanoid robots.

Future directions

The development of FACE is a long-term project that will evolve as new technological breakthroughs in materials engineering, control and other fields are made. The individual modules comprising FACE are under development, and their assembly will lead to new technological problems, which we are currently tackling; for example, the integration between artificial vision, the eyeball system and artificial skin, and the integration between artificial actuators and piezoresistive sensors. Interestingly, the piezoresistive sensors described in the section *Kinaesthetic proprioception* are much less sensitive to variations in electric fields than piezoelectric sensors. This is an advantage since they will require less rigorous shielding from the high electrical fields needed for actuating dielectric elastomers. In any case, should the processes of sensing and actuation interfere with each other, they can be effected at different instants since the frequencies of electronic acquisition and stimulation are far greater than those required for perceiving and generating expressions (the order of several milliseconds).

In the immediate future, attention will be focused on the use of the FACE system in therapy for people on the autistic spectrum; however, the concept of a believable humanoid display has far-reaching implications. Indeed, implications and applications of the whole system, or even of sub-aspects of this research, could potentially span a wide variety of fields. These can range from posing the basis to introduce new channels of interactivity in other 'intelligent' artificial systems, exploring possible medical applications or exploiting more refined expressivity for the movie industry's needs, to philosophical and psychosocial implications, or possible areas of inter-exchange with neurosciences. Moreover, it can be predicted that once the technological building blocks for constructing a believable facial display are developed and refined, the assembly of a whole mechanical android could become a real possibility.

To endow such a system with the elusive quality of believability, reducing 'expressive noise' and disturbance in the interaction with the observer, it is our opinion that three essential elements should coerce in a synergetic fashion. It is the fusion of these three elements that can contribute to design a framework for lifelike artifacts. First, the choice of the real material to be used to build the system is crucial. As described here, we must borrow from the advances made in the past few decades in polymer science and new breakthroughs in smart biomimetic materials research. In biological systems, the basic building materials are soft gel-like macromolecules. From a physical point of view, they are lowly materials, floppy, imprecise, noisy and lossy. On the other hand, they are versatile and can be used for transduction, sensing, conduction and actuation (De Rossi and Osada 1999). An important feature of biological tissue is its multicomponent and bi-phasic nature. This endows it with nonlinear properties and wide dynamic ranges. To be believable, then, the artificial entity must be constructed using materials with, amongst other biomimetic features built in compliance, nonlinearity and softness. The second 'must' is to confer the entity with the necessary humanlike mechanical behaviour to obtain lifelike motion. Anthropomorphic mechanics and control attempt to replicate the characteristic features of human movement: many degrees of freedom, high dimensionality of the control space and redundancy. Achieving this requires not just the appropriate choice of actuating materials (slow-twitch and fast-twitch actuating fibres), but also the appropriate choice of variables and frame of reference with which to describe and predict humanlike dynamics. The third element borrows from the neurosciences. In accordance with Western thinking from the time of Plato, logic and reasoning have been placed on a pedestal, and emotions and passions considered as inferior animal processes. Two major shifts in thinking in the neurosciences have recently emerged. First, the brain is now considered as a predictive organ, in which consciousness emerges from different levels: the 'primordial' protoself, the core consciousness and the extended consciousness (Damasio 2000). Second, logic and reasoning are driven and assisted by emotions, so the two are now on an equal footing. Moreover, the study of the relationship between perception, sensing and action suggests that perception and cognition are inherently predictive, allowing us to anticipate the consequences of current or potential actions (Bernstein 1967). Thus, we can describe the brain as a simulator that is constantly inventing models to project onto the changing world, models that are corrected by steady, minute feedback patterns arising from kinaesthetic and proprioceptive sensors in interactions with the environment. This process of interrogation and updating position enables us to navigate the world around us with the minimum of neural processing (Berthoz 1997). On the contrary, current thinking in robotic control is dominated by a completely different paradigm, which separates the domains of sensing, action and control with obvious engineering consequences of excessive time and computing. We are still far from reproducing these features in man-made systems; however, it is essential to keep these paradigms in mind when designing biomimetic artifacts. Technically and theoretically, the culmination of the process might be a revisited form of the Turing test, with the human face and the artificial FACE undistinguishable, when silent, to a human observer. We could, for example, imagine a test that could be used to validate the work done by a facial display; in other words, a figure of merit for 'believability'. Let us rephrase Turing's question in our context: is it true that a facial automaton built by adequate materials, with a suitably large database of expressions and equipped with appropriate controls, can be made to play the imitation game so satisfactorily as to fool a human judge? What is generally understood today when one talks about the Turing test could then assume the following form: let's imagine in a room, a human, we name him Judge, and two counterparts of which he can only see the faces. One is a human, A, and the other is the FACE mimicking A's emotional responses. Judge's task is to find out which of the two candidates is the machine and which is the human, only by looking at their facial expressions. If the machine can 'fool' Judge, then the task of conferring believability to FACE can be said to be satisfactorily achieved. In the engineering and AI (artificial intelligence) communities, this can be considered as an ultimate goal and, at the same time, as a method to measure the advancements obtained. Given the complexity of human communication and emotional life, this goal, if at all attainable, is still a long way away as far as man-made artifacts of this kind are concerned. In our interdisciplinary team, discussion about this subject is still open, with some of us also posing ethical and philosophical questions about the point. One is, given the crucial role of emotions and their expressions in regulating human identity and social exchange, should 'perfect believability' ever be desirable? This question should be reconsidered not only ethically but also on the basis of the specific knowledge human sciences have accumulated about our species. The second is that exploring lifelike systems in depth might also mean keeping our minds open to the possibility of renewing and evolving models of thought towards new forms and creative dimensions that may be previously unimaginable, and being aware of the risks the adventure may imply.

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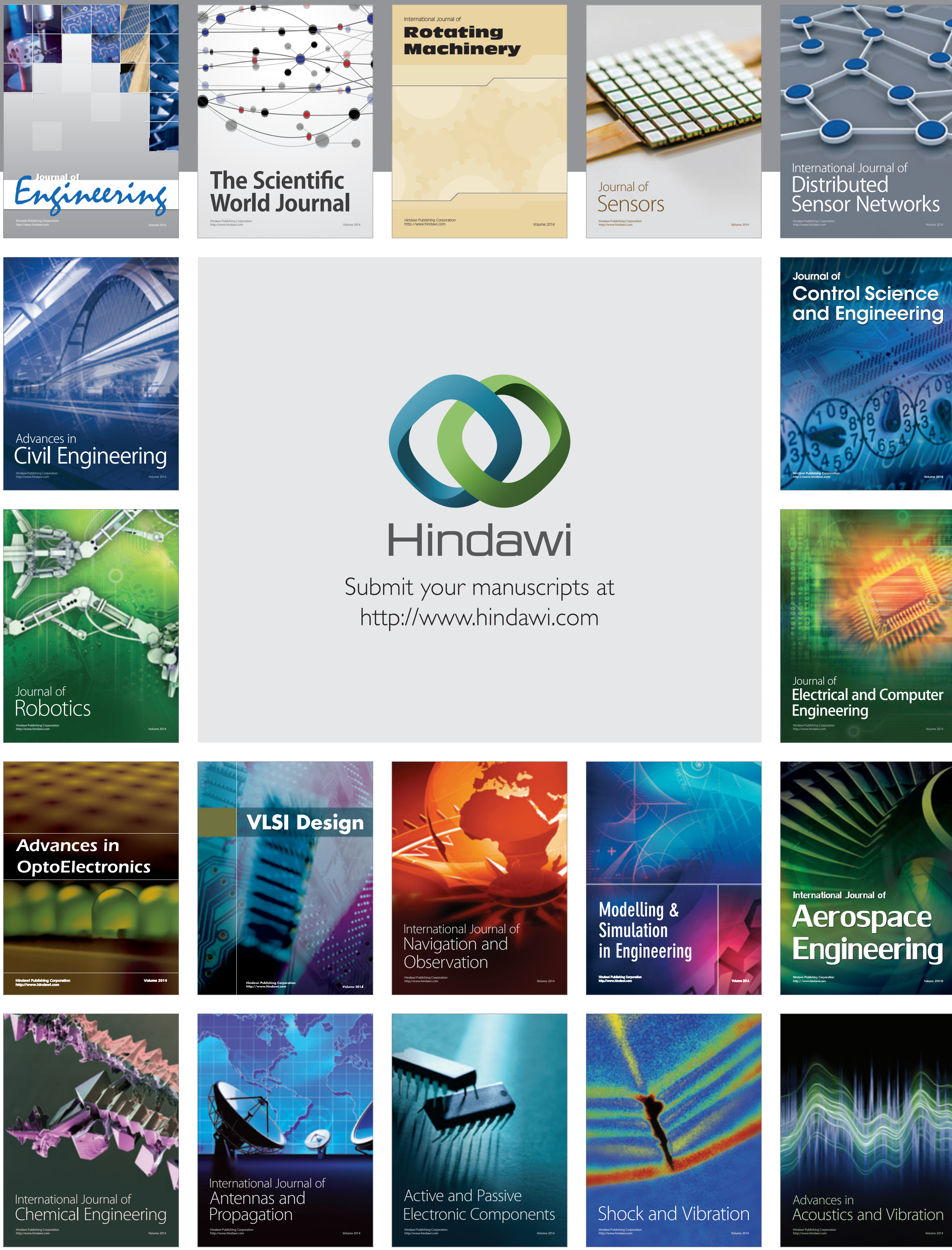
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