Robot Assisted Facial Expressions with Segmented Shape Memory Alloy Actuators

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Abstract: This paper introduces a robotic technology based supporting device, the Robot Mask, to enhance facial expressiveness and support physiotherapy for facial paralyzed persons. The wearable device, which consists of Shape Memory Alloy (SMA) based linear actuators, functions by pulling the facial skin towards anatomically selected directions. Since facial expressions are silent, SMA were selected over electrical motors.

This paper introduces a compact and fully controllable actuation unit with position feedback and a novel controlling scenario that uses the selected hybrid actuation of bidirectional multi segment SMA wires in series to pull the wires. When designing the actuators, a biomechanical analysis was conducted to find anatomical parameters of natural smiles, and the Robot Mask was evaluated for its suitability as a facial expression supporter.

Keywords: Shape Memory Alloys, Facial paralysis, Facial Expressiveness, Silent Actuation, Segmented Hybrid Control, Neuro-robotics.

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1 Introduction

This paper introduces the design of Robot Mask to support rehabilitation for hemi-facial paralysis. In this paper we mainly address the design criteria and the development of Robot Mask with a novel SMA (Shape Memory Alloy) based actuator.

Facial expressions, which are controlled by the electrical signals sent through the facial nerve; the seventh (VII) of twelve paired cranial nerves, are produced by the actions of the facial muscles (1).
However, due to various medical conditions, these voluntary muscle activities can sometimes degrade or even disappear, resulting in facial paralysis. The most common cause for the facial paralysis, the Bell’s Palsy, which was previously considered idiopathic but recently linked to latent herpes viruses, herpes simplex type 1 and herpes zoster, accounts for almost three quarters of all acute facial palsies. Overall it records 0.5 per year per 1000 with a recurrence rate of 7% and a life time prevalence of 0.64% to 2.0% (2). Other common causes for facial paralysis include virus infections, trauma, tumor and Neonatal conditions though it could even be congenital. Although the facial paralysis could occur at any age with both male and female, the tendency seems to be higher with the 15 to 45 age group and pregnant women (3; 4).

The effects of facial paralysis could be either temporary or permanent. Furthermore, the affected area could be distributed or concentrated to a small area and unilateral or bilateral. In the case of temporary paralysis, the average time of recovery can vary from 15 days up to four years. Apart from being facially less responsive, the paralysis can dramatically change the shape of the face with cosmetic and functional sequelae such as oral dysfunction, muscle contractors, nasal obstruction, disguise, dysesthesia and synkinesis (4; 5). Further, in unilateral or hemi-facial paralysis, the drooping of the ipsilateral face due to absence of baseline muscle tone and the consequent deviation of the nose to the contralateral side of the face could result in loosing the symmetry of the face (6). Furthermore, due to the inability to purse the lips tightly it can result in difficulties in eating, drinking and talking. It can also cause tear disorders, and the inability to blink or completely close the eyelid makes the cornea of the eye vulnerable to dryness.

Although the available medical support can speed up the healing process (2; 7; 8), as temporary paralysis sometimes can last up to 3 to 4 years, it is necessary to have other means to provide immediate relief. Furthermore, since conventional treatment methods are not capable of completely recovering the expressiveness of a permanently paralyzed face, other innovative techniques are required to support the facial expressiveness. Despite the advancement of biomedical engineering, not much effort has been made to address the facial paralysis, in terms of robotics. Under these circumstances, we propose the development of Robot Mask to support expressiveness of facial paralyzed patients during their rehabilitation process. The Robot Mask aims to improve the quality of life by providing a non invasive wearable device to recover and enhance facial expressiveness. With the Robot Mask, the facial expressions are generated by pulling the facial skin through wires externally attached to the skin. The system explained in the paper mainly targets the rehabilitation process of facial paralyzed patients. However, it could also be used as a cosmetic and health care management tool for the ageing society and a tool for expression training.

In this paper, we address some of the fundamental design questions: how to pull the skin, what type of actuators to use and how to connect them to the face, what are the expected performances from the actuators and once the actuator is designed, what is the criterion to control skin displacement and how to guaranty safety. By considering natural facial expressions, which are silent and the amount of expression change is intentionally controllable, we established silence and controllability as our most important requirements. Based on findings of Vaiman et. al (2005)(9), Sugimoto et. al (2007)(10) have suggested that visual and EMG biofeedback can be used to improve the effectiveness of neuromuscular retraining. We propose to extend this idea: to use EMG not only as biofeedback for targeted muscle training, but also as the basis for actuation parameters and expression timing.

In this paper, we first introduce our approach to smile recovery and the design requirements for the Robot Mask. We then introduce the design of a silent actuator to support facial expressiveness. By taking smile as the
design target, we explain the necessary requirements for the actuator and we evaluate the proposed actuator in terms of response, reproducing the profile of a natural smile and intention-based controllability using bioelectrical signals. In this research, the experiments, which involve human test subjects, were conducted with the informed written consent of the subjects.

2 Robot Assisted Smile Recovery

In recent years, assistive robotics have been used in an increasing number of applications that assist activities of daily life. Most of these devices such as prosthetic limbs and exoskeletons emphasize on supporting the physical functions of human. Nevertheless, in order to have a healthy as well as a happy society, supporting cognitive functions are equally important.

With the Robot Mask, physical support is provided by pulling the facial skin, and to achieve that, flexible wires are attached to the face with their other ends connected to linear actuators. A head supporter is used to mount them and other necessary peripherals (Fig. 1). In order to create facial expressions by pulling the skin, it is necessary to establish suitable pulling points and directions. One approach we considered was a grid based pulling system, which is similar to the human modeling methodology generally adopted by the computer aided graphics designers. However, realizing this through hardware requires a large number of actuators. On the contrary, following the human anatomy not only minimizes the required number of actuators, but also allows us to use the inherent characteristics of facial skin, i.e. the facial tissue resists deformation (turgor) and therefore appearance changes are always constrained by this characteristic. Hence, even with a smaller number of pulling points it could be possible to obtain natural looking skin deformations. In the Robot Mask, pulling points and the pulling directions closely follow the human facial anatomy so that we could use a displacement mechanism similar to the natural system. Furthermore, unlike skeletal muscles which often have pairs to produce opposite action, muscles of facial expressions are often unpaired and facial tissue and the muscle tension in the contralateral face control the return to a resting state. Therefore we assume mere releasing of pulling force is enough to return to neutral face. When connecting pulling wires to the skin, the connecting area could basically take two shapes: point based or distributed. However, by considering skin characteristics, we decided to use point based pulling. Later, in section 4.4, by using 3D displacement analyzing methods, we show that point based pulling can produce distributed effects similar to that of natural facial expressions.

![Figure 2](image.png)

Figure 2 Mouth corner displacement along the zygomaticus major direction during smiling of five subjects

2.1 Design considerations

The Robot Mask relies on physical interaction to create facial expressions. When the assisting device is in physical contact with the user, safety of motion becomes extremely important. With linear actuators, the maximum actuation distance, which is a critical factor for the safety, is fixed by the design.

In order to obtain silent actuation, a novel Shape Memory Alloy (SMA) based actuator, namely SIAC, was developed for the Robot Mask. The SMAs are controlled by Joule heating based thermal energy and occurs without any audible noise.

During social interaction, timing of expressions plays an important roll. The expression timing is based on the individual’s intention, and in the Robot Mask, this intention based control is achieved by using the bioelectrical signals on the facial skin. A standalone microprocessor is used to analyze bioelectrical signals.

Since the device can be effectively used as a support tool for rehabilitation, non-invasive techniques are used to attach pulling wires and sensors on to the face. Furthermore, any obtrusive device on the face is socially undesirable. Hence the actuator mounting and supporting part was made less obtrusive and the pulling wires and their attachments were made transparent.

2.2 Technical Requirements

**Displacement requirements:** We found that the amount of displacement varies for different expressions and different locations and the maximum for an exaggerated smile was 21 [mm] near the mouth corner, although typically it is much less (around 10 [mm]) (11; 12). Considering the various degrees of amplitudes for smiles, it was decided to have point-to-point controllability of the order of 1 [mm].

**Actuation rate requirements:** Fig. 2 shows the smile profiles of five subjects. The subjects were asked to smile and hold the smile for a self-comfortable short duration before reverting back to neutral. As the focus during this stage was to analyze the velocity profile, the subjects
were not given any specific trigger command. However, in Fig 2, the starting point of the profiles has been synchronized for better visualization. For analyzing, each subject was asked to make 5 smiles each, in front of a 3D motion capture system (NaturalPoint Inc. OptiTrack) with 3 [mm] diameter capturing markers placed at the mouth corner. The data were processed offline. By studying slow and fast voluntary smiles of the 5 subjects (3 male and 2 female, age 25.8 ± 5.1, 10 trials each) we noticed that for a typical random smile, from neutral to smile, the absolute displacement near the mouth corner along the zygomaticus major muscle direction has a rapid onset of 47.8 ± 21.8 [mm/s] followed by a slow settling period resulting in a total expression transition rate of 19.1 ± 7.9 [mm/s] and an expression transition time of 0.67 ± 0.26 [s]. With faster smiles, the smile transition rate showed significant differences among the subjects with trends not showing any correlation between the neutral to smile transition rate and the total transition time. Furthermore, the subjects also showed significant variations among their expressions. Fig. 3 shows the variation of total smile transition time for the five subjects when the subjects were asked to make 5 relatively fast smiles. This indicates that, smile profiles could be fairly inconsistent, and therefore, an artificially created smile does not required to have a strict target profile.

**Force requirements:** The pulling force depends on the amount of displacement and based on previous studies on facial biomechanics, in order to pull the skin, an actuator needs to have a maximum load carrying capacity of 140 [gf] (11; 12). Furthermore, by measuring with a force gauge (IMADA Inc. ZP-20) we found that for the region of rapid actuation, they need to have a load carrying capacity of about 0.8 [N] (Fig. 4).

### 3 Robot Mask

The Robot Mask consists of a head supporter, a pulling wire arrangement, a bioelectrical signal extraction and processing unit, motor actuation units and a power supply unit (Fig. 1). Each motor actuation unit has its own built-in dedicated control unit and a common controller is used to integrate them into the main system. The basic working principle of the device is the pulling of facial skin through the use of wires attached to the facial skin and the wires are pulled by the SMA based SIent ACTuation (SIAC) units. Each SIAC unit consists of a dedicated controller that facilitates the point to point feedback control of facial skin displacement with a resolution of ±1 [mm], which is well within the 0.25 [cm] lateral movement considered in the House-Brackmann score (14).

In the current study, for simplicity, we concentrated only on the oral group of facial muscles used for smiling: the zygomaticus major, zygomaticus minor, risorius, platysma, and the depressor anguli oris (Fig. 5). Movement are controlled by using bioelectrical signals from the contralateral side of the face. This approach is based on the cross-facial nerve grafting technique, which is used to generate symmetrical facial expressions on hemi-facial paralyzed persons (5). Fig. 5 shows the five pulling points with circles and the six pulling directions with arrows, and the six pulling actions are identified by their pulling points and the pulling directions respectively. Action 1 denoted by (1,1), actions 2 and 3 denoted by (2,1) and (3,1), action 4 denoted by (4,1), action 5 denoted by (5,1), and action 6 denoted by (4,2) are used to emulate the movement of zygomaticus minor, zygomaticus major, risorius, platysma, and depressor anguli oris respectively.
3.1 Head Supporter

The head supporter provides the basic structure of the Robot Mask. The back-pack carries all the SIAC units, controllers and the power units. The displacement motion generated at the actuators is transmitted to the skin via pulling wires sent through the tubes. The head supporter also serves the purpose of accommodating the pulling towards the directions of the five supported facial muscles and mounting of electrodes for biorobotic control. Considering the obtrusiveness, the bioelectrical signals, which mainly consist of surface electromyographic (sEMG) signals, are acquired not on the front of the face but near the parotid gland of the contralateral face (Fig. 5).

3.2 Silent Actuation unit

3.2.1 SMA based Actuators

Since the SMA phase transition is completely silent, they are ideal for the actuators for facial expressions. However, non linearities and slow cooling due to hysteresis behavior of the phase transformation makes it difficult to control them (15; 16). In order to overcome this issue, Asada et.al. (2003) have proposed an actuator which is immersed in a flow of water (17). However, the relatively large size of that cooling unit makes it undesirable for the current application. Another possibility would be the use of peltier devices to cool the SMA wire (18; 19). However, with the peltier devices, if the heat is not removed from the warmer surface, due to the heat transfer from the warmer surface to the colder surface, the colder surface starts to get warmer and could even become warmer than the atmospheric temperature. In order to use them effectively, some other heat removal mechanism such as a heat sink and/or a fan is required. However, such usage essentially contradicts the fundamental concept of silent actuation. In order to overcome above drawbacks, we propose a bidirectional multiple SMA segment actuator and a hybrid-controlling algorithm which can benefit from active forward and return strokes, in contrast to passive cooling.

SMAs show a high strain at martensite: the low temperature phase and a high stress at austenite: the high temperature phase. Generally the stress loaded SMA elements are brought back to original shape by Joule heating. As SMAs provide a high force to weight ratio, they facilitate the designing of very lightweight actuators. This particular 0.62 [mm] diameter Ni-Ti-Cu based SMA are used in the actuators (15; 16). In this study, helically wound 0.15 [mm] diameter helices have a specific heat values of 6.1 [cal/mol°C] at martensite low temperature phase and 8 [cal/mol°C] at austenite high temperature phase (20), and under normal working conditions the actuation elements were found to be operating at an average temperature of 68°C (the temperature data were recorded using a chromel-alumel K type thermocouple and a A&D Inc. AD-5602 thermometer). Although, compared to SMA fibers, SMA helices are not superior with respect to load carrying capacity, they are capable of producing large kinetic distortions of 100% or more.

3.2.2 SIAC Design

Initially we developed an SMA based actuator with feedback control to pull the skin. The actuator consisted of one SMA segment and the skin was pulled by contracting the SMA through Joule heating and brought it back to neutral under self weight of load by letting it to cool down naturally. With this actuator we found it is possible to obtain fast contractions with reasonable controllability (steady state error less than ±1 [mm] for step inputs of size over 6 [mm]). However, due to the passive nature, the return stroke took much longer and due to high thermal inertia, overshoot during fast actuations, in particular with small step inputs, were fairly large (350-500 [%]). Consequently, we decided to develop a bidirectional actuator so that both the contraction and the expansion could be controlled actively. However one issue with bidirectional actuators is SMA needs some time to cool down and therefore it’s hard to move against the already contracted SMA. In order to overcome this problem we decided to use a segmented bidirectional architecture.

Fig. 6 shows the design of the SIlent ACtuation unit (SIAC). It consists of five slider elements: main slider...
The Controlling algorithm: Although bidirectional actuation based SMA actuators have been tested by some researchers (20), a reasonable solution to the problem associated with the relatively slow cooling rate of SMA has not been found yet. For instance, we found that, when heated from a 5 [V] electrical supply, the 0.15 [mm] diameter and 40 [mm] long spring wound SMA wire used in the current study, on average exhibited a cooling rate of 3.3 [°C/s] opposed to relatively high heating rate of 6.5 [°C/s]. To overcome this problem, a hybrid architecture of segmented SMA in bidirectional actuation that can conveniently generate both the motions: expansion and compression was tested in this study. Fig. 7 illustrates the components of the multiple SMA actuation model.

Fig. 8 shows the complete block diagram of forward and return path multiple SMA hybrid control system. A 10 [ms] sampling interval is used in the microcontroller (Microchip Inc.). The calculated PWM duty ratio is sent to the Logic MOSFET driven voltage drive and the actuation elements are driven directly from the 5 [kHz] PWM signal. A reflective linear encoder (Avago Inc.) is used for the feedback and a software algorithm of four counts per pulse is used to interface the encoder. The feedback is taken at the main slider and the gain \( K_f \) is used to represent the 600 counts per inch scaling factor of the 150 [LPI] reflective linear encoder.

**Actuation Conditions:** Six different configurations: A, B, C, D, E, and F are used to drive the SIAC unit. Cases A, B and C aims to move the main slider towards the forward direction and cases D, E and F aims to move the main slider towards the backward direction. Table 1 outlines the complete set of driving configurations used in the controlling algorithm. \( V_i \) indicates the variable voltage at time \( t \).
Case A indicates a situation where ends of the middle segment for forward direction $F_2$ has only a very small potential difference, resulting in the actuation of almost only $F_1$ and $F_3$. The Joule heating provided from the small potential difference helps to keep the middle SMA stiff while ensuring a quicker cooling due to low temperature. In Case B, setting both the main slider and $V_2$ at ground potential results in actuating only $F_1$ and $F_2$. Case C corresponds to the actuation of only $F_2$ and $F_3$. The backward direction cases work in a similar manner, always enabling only two out of the three actuators that could generate the desired motion.

Principal of Control: When sampling period is $T$, denoting the reference input value $x_{ref}$ at the $k^{th}$ sampling interval as $x_{ref_k}$, the controlling approach could be mainly divided into two instances, $x_t \leq x_{ref_k}$ and $x_t > x_{ref_k}$, where $x_t = x(kT)$ represents the location of the slider at time $t$ and each of those two instances could be further subdivided into two more instances each as, $x_{ref_k} \neq x_{ref_{k-1}}$ and $x_{ref_k} = x_{ref_{k-1}}$. Following lists the calculation of PWM duty ratio:

1. (a) $x_t > x_{ref_k}$
   Enable pulse width modulation (PWM) on channels 3 and 4 ($V_3$ and $V_4$) and disable PWM on channels 1 and 2 ($V_1$ and $V_2$) enabling the backward motion while putting the forward motion actuators at rest.

   Calculate the current position as,
   \[
   \hat{x}_t = \begin{cases} 
   2x_{ref_k} - x_t & \text{if } 2x_{ref_k} - x_t \geq 0 \\
   0 & \text{otherwise}
   \end{cases} \tag{1}
   \]

   (b) $x_t \leq x_{ref_k}$
   Enable PWM on channels 1 and 2 and disable PWM on channels 3 and 4 (this enables the forward motion while putting the reverse motion actuators at rest)

   Set the current position as,
   \[
   \hat{x}_t = x_t \tag{2}
   \]

2. Using $\hat{x}_t$ as the current position and $\dot{e}_t$ as the corresponding error, calculate the controller output $U_k$ for the PID controller:
   \[
   U_k = K_p\dot{e}_t + \int K_i\dot{e}_t + K_d\dot{e}_t \tag{3}
   \]

3. Select “Actuation Case”

4. Load $U_k$ to PWM duty ratio controller

When the main slider is required to move backwards, current position is ahead of desired position. However, in this case actuation is done with $B_i$ segments and for them increase of current will result in reducing error hence for them it’s a positive displacement. With equation 1 current position is modified so that the backward PID can treat it as a positive displacement case.

Out of the six actuators, represented by $F_i$ and $B_i$ ($i = 1, 2, 3$), for $x_{ref_k} > 0$ only two actuators are active at any given instance. At the beginning, $i = 1$ and $2$ are selected as default working actuators by the “Actuation Case” process, whereas upon a change of slider moving direction, the subsequent working actuators are selected with respect to two conditions.

During normal continuous operation, a timer is initiated at the start of the motion of the main slider and a cooling flag $C^f$ is set at the overflow of the timer. When the direction of motion of the main slider is changed, SMA segments of the opposite side are actuated and at that time if $C^f$ is set, that means the SMA segment, which were in operation during the last operation, had enough time to cool down and therefore the same set of segments are used for the current operation. However, if $C^f$ is still not set, then the actuation case is changed, allowing more time for one of the two segments to cool down. In that case, the next set of actuators are selected cyclically between the cases $A \rightarrow B \rightarrow C$ or $D \rightarrow E \rightarrow F$. This was done to allow uniform cooling among SMA segments and to limit over using of any one segment during continuous operation. As it can be seen from table 1, by following this cyclic arrangement, any segment will get a cooling period after a maximum of two operations. When the slider is moving in one direction the SMA wires intended for the opposite direction are maintained at unused state. Nevertheless, during operation for which $x_{ref_k} = x_{ref_{k-1}}$, in order to maintain smoothness, the PID control output for the unused segments were also updated. This helps to reduce overshoot and fluctuations.

Fast Actuation and Prevention of Overheating:
At the beginning, the PWM modules are initialized with a 100% duty ratio, making it possible to pump the largest possible current into the SMA wire therefore achieving the fastest possible initial actuation. However, during operation, the duty ratios are adjusted by the PID control unit to achieve desired position control. Nevertheless, when the actuators are used in the same direction for a longer duration, due to the payload followed by the cooling down of low-powered SMA segment and the consequent loosening of stiffness, the low-powered segment is likely to elongate, negating the effect of other two SMA segments in action. This loss of contraction will result in the PID controller increasing its duty ratio on the two high-powered actuators. Persevering such high duty ratios are likely to cause the SMA segments to overheat. Hence it is necessary to do a load balance and the cooling flag $C^f$ and the the direction change flag $D^f$ are used to solve this. $D^f$ is set when the direction of motion of the main slider is changed and if $C^f$ was set before $D^f$, it implies that the current set of SMA segments are being used for too long and that forces a change in the actuation condition while maintaining the actuation direction. If $D^f$ was set before $C^f$, the direction of motion is reversed and the
both the flags are reset after loading $U_k$ to PWM duty ratio controller. This mechanism will help to maintain the stiffness of all the loading direction actuators above a critical level while ensuring that no SMA segment will be used for more than twice the minimum required cooling period.

4 Experiments

Four experiments were conducted to evaluate the actuator and the validity of Robot Mask design. First the actuator performances were evaluated using a varying step input. Then, since the slider displacement is taken as a measure of skin contraction in the control algorithm, experiments were done to evaluate the relationship between slider displacement and the actual skin displacement. Next, by using profile data of a natural smile, artificial smiles were reproduced on the face of five subjects. Finally, by using 3D image comparison technology, the effect of point based pulling was evaluated. When evaluating intention based control, since it might be difficult for a healthy subject to smile unilaterally, regularly, we tried the smile sharing by placing the sensors on one subject and the Robot Mask on a separate subject.

4.1 Step response

In order to evaluate step response, for both forward and backward directions, we evaluated the tracking characteristics for a variable level up-down step input, and the results were compared with the tracking characteristics of a unidirectional actuator which tracks a variable level step-up input. Unidirectional actuator is with a single SMA segment in the forward direction (oppose to 3 segments each in forward and backward directions of the bidirectional actuator) and brought back to the neutral under the self-weight of the load whereas in the bidirectional actuator it is both under self-weight and active pulling towards backward direction. The same PID controlling algorithm used for the unidirectional algorithm is used to control the forward direction segments in the bidirectional algorithm. Since the bidirectional actuator is capable of bringing the actuator back to neutral actively, we chose the step up and down reference to test the bidirectional actuator.

The reference for the unidirectional actuator is a stair type step-up input with a step height of 2 [mm] (Fig. 9), and the reference for the bidirectional actuator is a 1/4 [inch] up followed by a 1/6 [inch] down with a step size of 3 [s] (Fig. 10). Experiments were done by hanging a 110 [gf] constant load to the pulling wire of the actuators. Gain parameters, $K_p$, $K_d$ and $K_i$ of 0.85, 0.5 and 0.75 and 0.6, 0.45 and 0.6 were used on forward and return control paths of the bidirectional actuator. The gain parameters were selected based on manual tuning, and considering the skin weight support, slower parameters were used in the return path. Since overshoot is not a serious problem as the controller logic was designed to change the SMA segment direction at the reference point, the initial PWM and PID gain parameters were selected to have a fast rise time. Hardware based and software controlled encoder feedback gain was set to 600 pulse per inch (ppi). In average, the actuator exhibited a faster rise time of 1.38 [s] and a smaller percentage overshoot of 1.6 [%]. By comparing this with Fig. 9, it can be seen that bidirectional actuation, while achieving a shorter start-up delay, not only tracks a diminishing step but also significantly reduces the overshoot.

However as it can be seen from Fig. 10, for long time continuous operation, we observed that from the fourth cycle onwards the bidirectional actuator started to go out of synchronization with the reference input. Ideally, when the actuation case is changed, the non energized segment of the previous cycle needs to be back to the original expanded state. However, since we observe the position feedback only at the main slider we realized that due to non-linearities in SMA there will be some deformation left in the non-energized segment and over time this get accumulated, resulting in decreasing the possible contractable length of the segment. This problem can be overcome by bringing the segments back to their original neutral state after four cycles and in the Robot Mask this is more likely to happen naturally. Note
that this type of continuous up-down actuation without returning to zero is uncommon with facial expressions and in particular during rehabilitation physiotherapy.

4.2 Skin contraction and Sensor feedback

The control system of the Robot Mask uses an incremental type linear encoder with a resolution of 600 [ppi]. However, as shown in Fig. 8, the feedback measurement is taken at the slider and not on the face. When pulling externally using wires running over the skin, there is a possibility of pulling wire slightly sinking into the face, and due to this there is a possibility of sensor not providing an accurate reading of the facial displacement. The actual displacement will also be affected by the characteristics of the skin-wire joint. Hence it is necessary to investigate how good an estimator $\hat{y}$ is for the actual skin displacement: $y$. This was analyzed through an offline comparison of the sensor reading for point to point control against the corresponding 3D displacement calculated from the 3D images of the events (Fig. 11). After placing markers over the skin-wire contact points, pulling actions (1,1), (2,1), (3,1), (4,1), (5,1) and (4,2) were performed with pulling amount discretely varying between 0 - 23 [mm]. The slider displacements were recorded directly from the encoder. The discrete 3D images of the events were captured using a 3D scanner (NEC Danae 100SP) and later, after reconstructing 3D images, actual linear displacements of contact points with respect to the neutral face were measured.

Fig. 12 shows the actual skin displacement amounts against the corresponding sensor readings of a female subject for the six different artificial actuation configurations. The results indicates slightly larger values for actuator contractions compared to their corresponding skin displacement values. A line fit through the origin showed a ratio of 0.89 between the actual skin displacement and the sensor reading. The coefficient of determination $r^2$ of the fit was found to be 0.95 and the standard error was found to be 1.31, indicating that a linear approximation is acceptable and for small displacements, it is reasonable to assume a one-to-one map.

4.3 Smile reproduction

25 set of experiments were conducted on five male subjects (age 26 ± 4.5, five trials on each subject) by attaching the actuator pulling wire to the mouth corner and evaluated the actuator reproduction of a natural smile profile. For the five subjects, on average, the actuator showed a rapid onset rate of $16.1 \pm 3.9$ [mm/s] and an expression changing time of $1.72 \pm 0.23$ [s]. The comparison of raw smile rates between natural and artificial expressions indicates that the artificial expressions in average take 1.05 [s] more to change from neutral to smile. This is mainly caused by the initial delay due to thermal inertia of the actuators. Nevertheless, with artificial expressions, the user starts to feel the moving of his skin within about 0.5 [s], which is about the starting delay of actuators. Furthermore, the fact that every individual has their own expression timing means the artificial expression dose not need to start exactly at the starting point of the natural expression. Therefore, in the plot, once the starting point for the artificial expression is advanced appropriately, it can be seen that the artificial expression could follow the profile of the corresponding natural expression (Fig. 13).
4.4 Distributed effect of point based pulling

As it was mentioned in section 2, since the pulling of the Robot Mask is point based, by using a 3D image analyzer, we evaluated the distributed effect of point based pulling against a natural smile. Fig. 14 shows the comparison between a natural (left) and an artificial (right) smile. The bottom row shows the skin protrusions and depressions of the smiling face with respect to the neutral face. The displacement variations are represented by using colours, with + and - indicating the protrusions and depressions of the skin respectively. The plots were obtained by first, aligning the neutral and smiling face images reconstructed from 3D stereo vision data and then, comparing the surface locations with respect to the neutral face. Aligning was done by matching the craniofacial landmarks: frontotemporale (ft), nasion (n), frontozygomaticus (fz), sellion(s), endocanthion (en), exocanthion (ex), orbitale superius (os), maxillofrontale (mf), zygion (zy), subnasale (sn) and pogonion (pg) of the two images: neutral and natural/artificial smiling. The artificial expressions were generated by using the pulling actions (2,1) and (4,1), simultaneously. Although the pulling was point based, as it can be seen from bottom right of Fig. 14, the human skin characteristics distributes the effect, and the skin deviation pattern similar to the natural smile confirms that point based pullings can effectively generate natural looking facial expressions. In order to qualitatively analyze skin displacements, by comparing 3D surface location data, we calculated the volumetric skin displacements of natural and artificial smiling faces against neutral face for the right hand side hemi-face.

For a natural smile, we found depressions and protrusions having volumetric displacements of 3.281 [cm$^3$] and 5.425 [cm$^3$] respectively and for an artificial smile protrusions and depressions having volumetric displacements of 4.937 [cm$^3$] and 2.990 [cm$^3$] respectively. Similarly for the area marked by the dotted spline in Fig. 14 we found the corresponding amounts to be 2.275 [cm$^3$] and 0.468 [cm$^3$] against 3.108 [cm$^3$] and 0.159 [cm$^3$] respectively (Fig. 15). Therefore it can be seen that for the vicinity most affected by the pulling, protruded and depressed volumes show fairly similar amount of skin deflections.

5 Discussion

5.1 Bioelectric Signal Based Control

The main target of bioelectrical signal based control is to obtain seamless control of artificially generated facial expressions and support the timing of facial
message signs needed for interpersonal communication. By acquiring bioelectrical signals from the contralateral side of a hemifacial paralyzed person and using them to actuate the artificial muscles of the ipsilateral side, we aim to artificially correct the baseline facial muscle tone, and to minimize the drooping of the ipsilateral face.

This bioelectrical signal based brain interaction provides seamless control of the robot mask while supporting the natural timing of facial message signs needed for interpersonal communication. Furthermore, depending on the strength of the bioelectric signals, signals of the ipsilateral face itself can be used for rehabilitation. The effectiveness of neuromuscular facial retraining with EMG in facial paralysis rehabilitation has already been confirmed by Cronin and Steenerson (21). Their study, involving 24 patients with an average onset of symptoms before the initiation of facial retraining of 32 months showed marked improvements in function, symmetry, and decreased synkinesis. The overall EMG readings after treatment (treatment durations varying from 3.3 to 15 months) showed symmetric or within 2 to 5 [µV/s] of the normal side.

By using bioelectrical signals acquired near the masseter muscle, we evaluated the intensity based controllability of constantly loaded unidirectional SMA actuator. Fig. 16 shows the raw bioelectrical signal (the upper graph), the reference for displacement, and the actual displacement for a 110 [gf] constant load. The vertical dotted lines partitions the time axis with respect to change of displacement control logic. Although this is not directly observable from the raw bioelectrical signal, by using the average and the variance of the raw signal, we were able to control the desired movement.

5.2 Performance evaluation

Fig. 17 shows the generation of expressions by using two actuators with feedback control.

5 Conclusion and Future works

In this paper, we introduced a novel robotics based approach to support expressiveness of the face. By carefully investigating the anatomical and biomechanical characteristics of a smile, we obtained the design parameters for the Robot Mask. Since facial expressions need to be silent, we developed an SMA based silent linear actuator; SIAC, that can effectively follow the profile of a natural smile. By using an approach of segmented bidirectional control with a high initial current injecting algorithm, we were able to achieve fast actuations in both directions. Updating controller parameters of the rested SMA segments worked as an annealing process, helping to improve the smoothness of the actuation. Furthermore, the compact and modular arrangement of the actuator provided higher scalability, which will be required when expanding the mask functionality to the corrugator and orbicularis oculi muscles of the face. With this actuator we obtained fast bidirectional actuations with a minimal overshoot. We also managed to generate facial expressions that could closely follow the profile of a natural smile. To obtain facial expressions, we used point based pulling of the facial skin, and by analyzing the skin surface variations, we confirmed that this produce distributed effects which are consistent with a natural smile.

The Robot Mask is portable, light-weight and self wearing. We already have confirmed through clinical studies that the users can wear the Robot Mask of their own. Nevertheless, we plan to continue our work on making Robot Mask even more compact in order to make it more comfortable and less obtrusive.

In the actuation controlling algorithm, based on manual tuning, a value of 5 [s] has been used for the cooling flag $C_f$. In the future, we plan to use a mathematical model of SMA wire to model the heat transfer into the SMA segments as well as the stiffness variation against environmental variables and optimize $C_f$ accordingly.

We also showed the use of bioelectrical signals of the masseter muscle to obtain bioelectrical signal based control. Currently we are working on developing distal bioelectrical signal recording to classify facial expression (22) and we plan to integrate it to the Robot Mask to enhance intensity based control.

In the current stage, when connecting actuators to the skin, we used 1 [cm] × 2 [cm], 10 [µm] thick polyurethane film type fixations. In order to obtain the most suitable parameters, we are investigating effects of size and shape of pulling wire fixations.
Future investigations also include the evaluation of the actuator response rate and effects of biorobotic control in facial neuro-rehabilitation as well as electrical nerve stimulation to innervate circular muscles, which are not realizable through linear pulling.

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