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Portable haptic interface with active functional design

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ABSTRACT

Haptic rendering is the process of computing and generating forces in response to user interactions with virtual objects. The interaction modality of haptic feedback gains more and more of importance for simulation tasks in virtual environments. However there are only very few portable haptic interfaces, with which the user can experience in a natural way the sensation of force feedback. The scope of this paper is to present a new portable haptic interface using shape memory alloy wires as actuators. Shape memory alloys (SMA), and especially the nickel-titanium compositions, offer a number of engineering properties available in no other material. The ability to respond with significant force and motion to small changes in ambient temperature and the capability to convert heat energy into mechanical work provide the designer with a new array of possibilities. Beside some application specific characterization of the actuator material with respect to energy consumption and dynamic behavior for loading, the mechanical layout of the interface is discussed in detail. To realize a light and compact design of the interface, a flexure hinge is considered as an essential part of interface.

Keywords: shape memory alloys, haptics, force feedback, virtual reality

1. INTRODUCTION

Virtual Reality is superior to other forms of human-computer interaction since it provides a real-time environment integrating several new communication modalities. These include stereo graphics, three-dimensional sound, tactile feedback and even taste and smell in the future. By providing such a rich and real-time sensorial interaction virtual reality makes the user feel immersed in the simulation or application he is running. As opposed to looking at the computer, the user feels surrounded by a synthetic world with which he can interact and modify⁶.

The realism of current simulations is also impacted by the lack of good physical simulation. The lack of haptic feedback in virtual environments removes a major information channel to the user. The term "haptics" comprises all kind of force effects onto the human body. Currently most data acquisition in virtual environments is with vision and with non-contact sensors such as sound. The information requirements of many tasks needing dexterous manipulation and the sense of touch such as remote control of a robot to locate and feel surface contours of objects is not met without tactile feedback⁶.

To provide sufficient realism, the simulation must include physical constraints such as object rigidity, mass and weight, friction, dynamics, surface characteristics (smoothness or temperature), and so on. As indicated in Fig.1 these requirements are very difficult to meet even if the haptic function is reduced only to the grasping of an object. Adding physical characteristics to virtual objects in turn requires both powerful computing hardware and specialized input/output-tools. These i/o-devices are worn by the user and provide tactile and force feedback in response to the VR simulation scenario⁶.

Major improvements in feedback actuators, sensors, and computing hardware must lead to miniaturization, less cumbersome haptic interface devices, and an increase in the user's safety and freedom of motion. These improvements thus lead to more natural, realistic, and useful simulations.

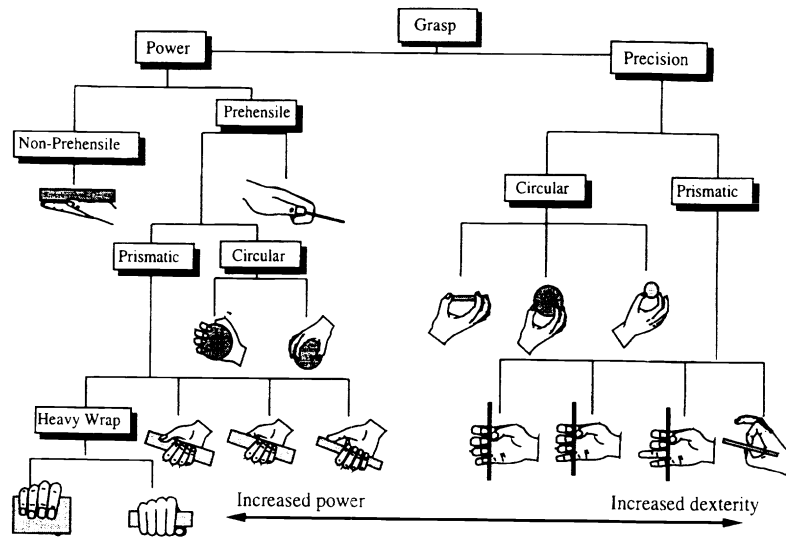


Fig. 1 Various hand grasp geometries¹

The objective of this paper is to give an overview over a development of a new portable haptic interface (PHI) device using shape memory wires as actuators. Special emphasis is given to design aspects.

Shape memory alloys have a considerable potential for broad field of applications. The use of SMA composites for vibration control has been successfully demonstrated^{2,4}. They can also be used for motion and shape control of structures to maintain a required shape or orientation for an extended period of time⁵.

2. SPECIFICATIONS AND REQUIREMENTS FOR A PORTABLE HAPTIC INTERFACE

There are numerous haptic devices available of which only a few could leave the state of prototype and were realized as commercial products. In most cases the design of the interface itself was the reason for this. Heavy constructions, which are only useable stationary, restrict the range of applications.

The advantage of nonportable haptic interfaces lies in their ability to off-load the actuator weight from the user. The disadvantage is a reduction in the user's freedom of motion, and thus in the simulation naturalness. To allow maximum freedom of motion for the user receiving haptic feedback from the simulation, it is necessary to use a portable force-feedback interface.

A portable haptic interface denotes an actuating or sensing structure that is grounded on the user's body (either on the back, chest, arm, or palm). Such portable masters are more difficult to design because there are limitations in overall weight and volume, dictated by the need to avoid user fatigue during prolonged simulations. This in turn implies high power-to-weight and power-to-volume ratios for the actuating system. Portable force-feedback interfaces can be classified according to their mechanical grounding as either arm exoskeletons, or hand masters⁶.

For a portable haptic interface, which is worn by the user similar to a data glove, the following general requirements are of concern:

- low energy consumption,
- low weight,
- effective energy conversion,
- simple design,
- safe use (electrical and mechanical),
- low manufacturing costs,
- comfort of use (easy calibration).

Due to relatively heavy actuators like step motors with a specific power of 50 W/kg, the mechanical host structure automatically results also in a heavy structure which can only be used stationary on a desk or must be mounted elsewhere. Therefore active materials like SMA-wires with a superior specific power of 200 W/kg promise appropriate characteristics for this kind of application.

3. CHARACTERIZATION OF THE ACTUATOR MATERIAL

Mechanical actuators are the control mechanism of machines. They convert energy of different type into mechanical energy, which is needed to do work against a load. The mechanical energy output of actuators are characterized by

- force/ displacement characteristics,
- linearity,
- dynamics,
- resolution,
- stroke,
- efficiency of energy conversion,
- volume to weight ratio
- reliability.

Beside the excellent specific energy of SMA the large actuation stroke of 5% was one reason to select this material as actuator. The bandwidth limitation of app. 5 Hz is not critical for this kind of application, because the opening and closing motion of the human hand is assumed to fit into the available bandwidth.

| Material | Bandwidth | Resolution | Spec. energy | Efficiency | Stroke |
|-----------------|-----------|------------|--------------|------------|--------|
| Bimetal | --- | 0 | 0 | --- | + |
| SMA | --- | -- | +++ | -- | +++ |
| Magnetostrictor | ++ | +++ | 0 | -- | 0 |
| PZT | +++ | +++ | + | ++ | --- |
| Electromagnet | + | 0 | - | +++ | ++ |
| Muscle | --- | -- | ++ | ++ | +++ |

Fig. 2 Qualitative assessment of different single-stroke actuators⁵

Because of the well known properties of the shape memory material, the nickel titanium wire FLEXINOL™, from DYNALLOY Inc. was chosen. Some material properties given by the manufacturer are summarized in Tab. 1.

| | |
|-------------------------------------|---|
| Diameter [mm] | 0.15 |
| Stroke [%] | 5 (with bias spring) |
| Actuation force [gms] | 330 |
| weight density [kg/m ³] | 6450 |
| Melting temperature [°C] | 1250 |
| Electrical resistance [Ω/mm] | 0.049 |
| CTE [10 ⁻⁶ 1/°K] | martensitic phase: 6.6 austenitic phase : 11.0 |

Tab. 1 Properties of the selected SMA-wire¹⁰

To get more information of the composition of the wire, a energy dispersive electron beam microanalysis was carried out, which shows that the wire consists of 51.16 at.% nickel and 48.84 at.% titanium. Some basic tests proofed that the wire was already prestrained by 5% by the manufacturer. For the wire used a tensile stress of 35 MPa is sufficient for the complete straining. The maximum stress in the wire was measured with 1245 MPa and an elongation of 9.3%.

Concerning the transition temperatures between the austenitic and martensitic phase slight differences compared to the manufacture data were found (Tab. 2). However it is important that the transformation temperature is high enough over the human body temperature.

| Property | Activation current [mA] | Temperature [°C] |
|-------------------------|-------------------------|------------------|
| Austenite-Start A_s | 210 mA | 59 |
| Austenite-Finish A_f | 230 mA | 64 |
| Martensite-Start M_s | 130 mA | 45 |
| Martensite-Finish M_f | 110 mA | 40 |

Tab. 2 Transition temperatures of SMA-wire

The wire shows the expected hysteresis loop with a transformation hysteresis width of 90 mA (Fig. 3). The relation between the transition temperatures and the current was determined:

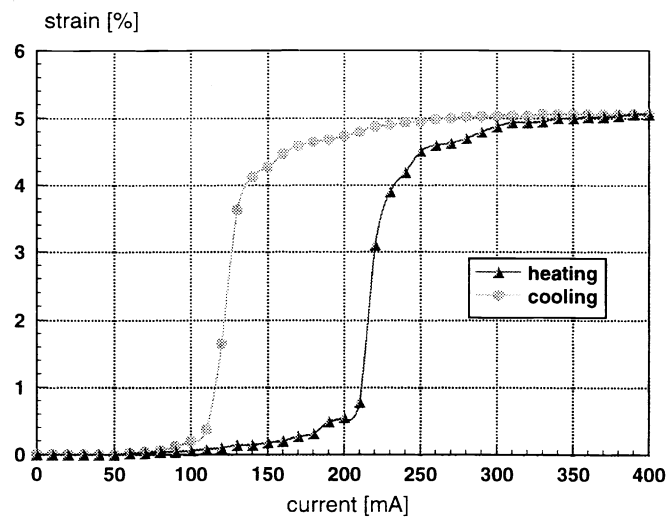


Fig. 3 Hysteresis loop of the SMA-wire¹¹

A current of $I=360$ mA results in the maximum strain of 5%. The transition (start to finish) needs a change in current of app. 10 mA. Moreover the relation between current and wire temperature was calculated and experimentally determined as well.

To judge the SMA-wires with respect to dynamic operation, the dynamic thermal loading and unloading is a very important issue. For that reason a current step was applied to the SMA-wire and the reaction (contraction) was measured as function of time. The output signal can be idealized as shown in the lower part of Fig. 4.

Moreover the time until the SMA-wire fully contracts is of interest. Therefore a step current load was applied to the wire at different levels at the time t_0 . At the time t_2 the wire has completely transformed to the austenitic phase.

Fig. 4 shows the time required to reach the transition temperature $A_f = 64^\circ\text{C}$. A current of 400 mA is sufficient to perform the contraction of the wire within 1 sec. This measured value confirms the data provided by DYNALLOY. If the current is further increased, the reaction also reduces, but approaches asymptotically to a limit reaction time of app. 400 msec.

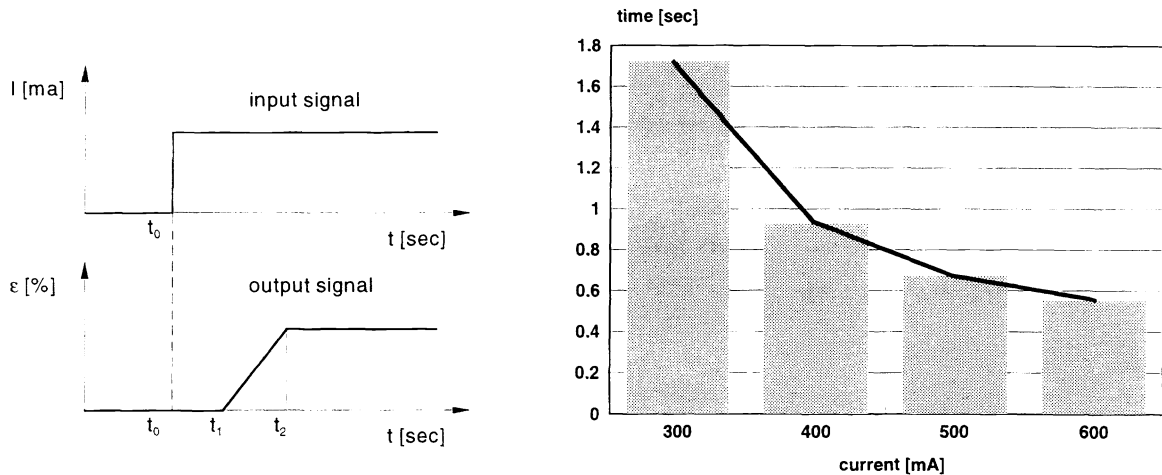


Fig. 4 Dynamic response of SMA-wire with respect to step loading¹¹

4. LAYOUT AND DESIGN OF THE PORTABLE HAPTIC INTERFACE

After Shimoga⁷ the maximum bandwidth with which the human finger can react to unexpected force/ position signals is 1-2 Hz. The maximum bandwidth, which with the human finger can apply force and motion commands comfortably, is in the range between 5 to 10 Hz. The maximum grasp force of a male is app. 400 N, of a female app. 230 N⁹. The global layout of the PHI is shown in Fig. 5. The objective of the interface is to restrain the closing motion of the hand. Therefore the motion must be transferred to a mechanical element, a Bowden control. The Bowden control itself is embedded into a glove and connected to a fingertip attachment and the lock element. In the case that contact between the user's hand and the virtual object occurs this element locks the motion of the Bowden control and thus also the further motion of the fingers. Moreover the position of the fingers must be known in order to detect possible contact situations. This information is needed to do a real-time collision detection in the virtual environment.

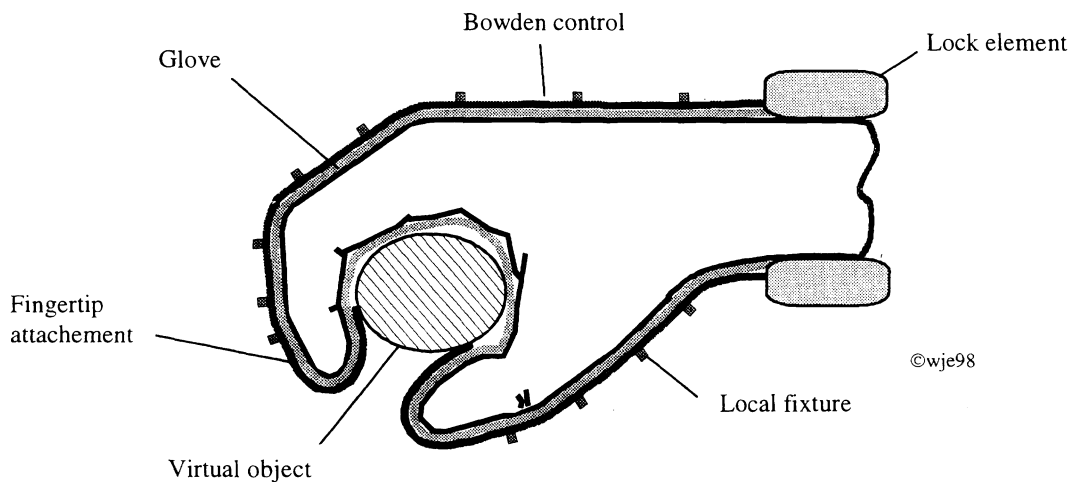


Fig. 5 General mechanical layout of the portable haptic interface (longitudinal section)

The essential part of the haptic interface however is the lock element. A longitudinal section of the lock element is shown in Fig. 6. The main component is the lever with a tooth head (1). It has the function to lock the motion of the toothed rack (2) in -x-direction. Therefore the SMA loop (2), fixed by a plug (5), is activated and the lever is deformed in z-direction. The

activation of the wire is only necessary to enable the locking, because the tothing is self locking. Therefore the energy consumption is relatively low. The flexure hinge is the bias spring to reset the SMA loop. Moreover the readjusting spring (4) supports the opening motion of the toothed rack in x -direction. The position of the toothed rack (3) is measured by an infrared phototransistor and an infrared led (10). The light of an IR led is emitted and reflected by a mirror (9), mounted on the moving toothed rack, and received by the infrared phototransistor.

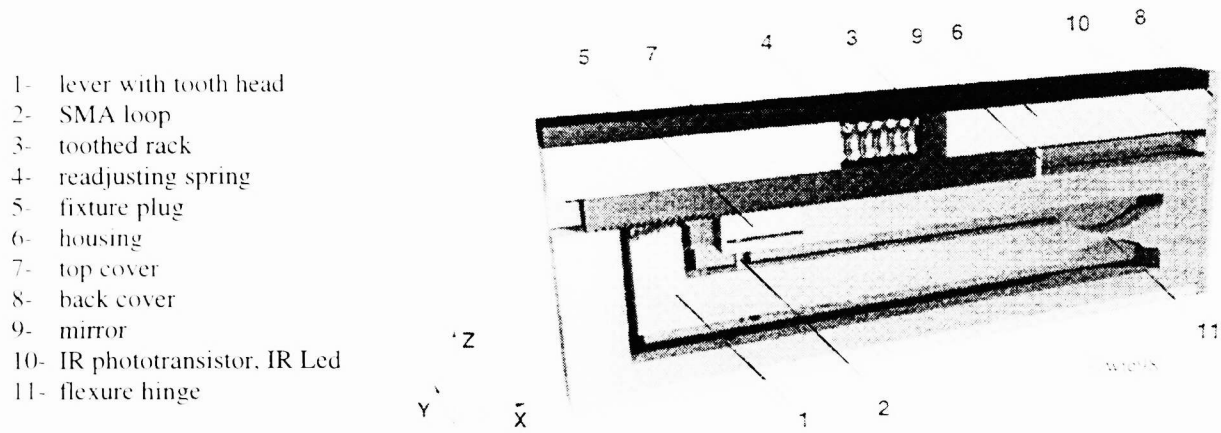


Fig. 6 Schematic representation of the lock element, longitudinal section

The bias spring for the SMA loop is defined by the bending stiffness of the flexure hinge (11). The basic design parameters of the flexure hinge are summarized in Fig. 7. With respect of the actuation force of the SMA wire the geometric parameters of the flexure hinge are determined. Beside the stress loading of the flexure hinge the effective stroke of the lever is of interest to ensure a reliable lock function.

Angle:
$$\Theta = \frac{2 K M R}{E I_x}$$

Correction factor:
$$K = 0.565 \frac{t}{R} + 0.166$$

Max. bending stress:
$$\sigma_{max} = \frac{6 M K}{b t^2}$$

Stress concentration factor:
$$K_t = \frac{2.7 t + 5.4 R}{8 R + t} + 0.325$$

Deformation:
$$y = \frac{2 K R l^2}{E I_x} F$$

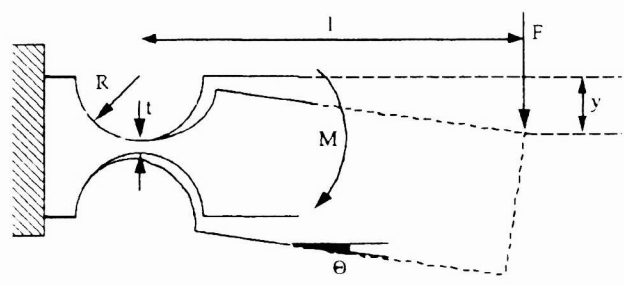


Fig. 7 Design parameters of a symmetric flexure hinge⁹ (see Position 11 in Fig. 7)

Assuming a total actuation moment $M=420 \text{ Nmm}$, a web thickness $t=0.8 \text{ mm}$, a width $b=6\text{mm}$ and a radius $R=5\text{mm}$, the stroke at the lever tip, made of steel, is app. 1mm . Fig. 8 shows the plot of tip deflection (stroke) and web thickness for his case. Thus the necessary stroke can be easily adapted either by the diameter of the SMA wire (actuator force) or by the web thickness.

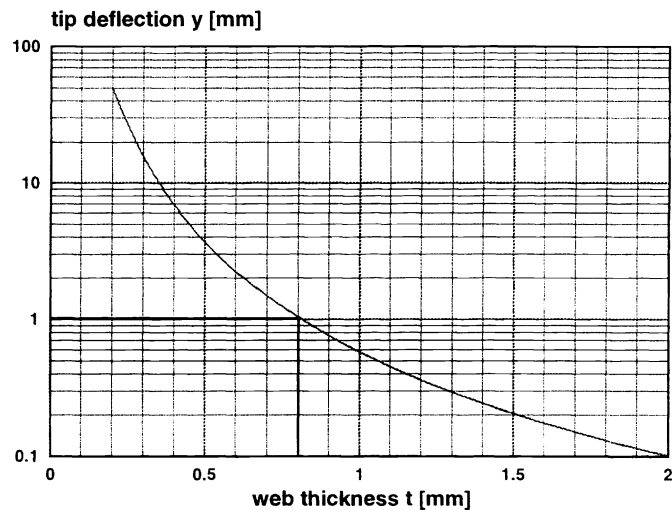


Fig. 8 Tip deflection vs. web thickness (radius $R=5$ mm)

5. SUMMARY AND CONCLUSIONS

A new mechanical design of a portable haptic interface has been presented. With respect to required stroke and low energy consumption, SMA wire has been selected as actuator. The presented design results into a total mass of the interface of app. 350 grams for all five fingers. The combination of the SMA wire as actuator and the use of a flexure hinge allows a compact design of the interface.

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