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HAPTEX

HAPtic sensing of virtual TEXtiles

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Thematic Priority: **Priority 2: Information Society Technologies**

Deliverable D5.2

Final Demonstrator and final integration report

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The HAPTEX Project Consortium groups the following Organizations:

ORGANIZATION	SHORTNAME	ROLE	STATE
MIRALab - University of Geneva	UNIGE	Coordinator	Switzerland
University of Exeter	UNEXE	Partner	United Kingdom
Scuola Superiore Sant'Anna	PERCRO	Partner	Italy
University of Hanover	UHAN	Partner	Germany
Tampere University of Technology	SWL	Partner	Finland

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1. Introduction

This report describes work in Workpackage 5: *Multimodal integration and validation*. The original project workplan envisaged the construction and evaluation of a single system, in pre-final and final versions. However, the workplan has been modified to include progressive stages of system development (see Figure 1), as follows:

Development level DL1: 2-digit force feedback and visual
Development level DL2: 1-digit tactile (palmar mechanism) and visual
Development level DL3: 1-digit force feedback, visual and tactile (palmar mech.)
DL3 not implemented -- replaced by DL4a
Development level DL4a: 1-digit force feedback, visual and tactile (dorsal mech.)
Development level DL4b: 2-digit force feedback, visual and tactile
Development level DL5: hand exoskeleton for force feedback, visual and tactile

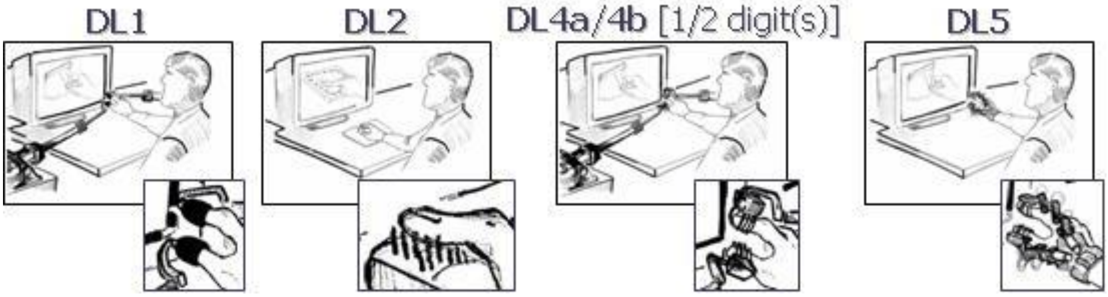


Figure 1. Development Levels – progressive stages of system development for the HAPTEX hardware and associated software.

This report relates to system development and validation for development levels DL4 and DL5. A previous deliverable (D5.1) relates to DL1 and DL2.

2. Development level DL4

2.1. Summary of system development for DL4

Development level DL4 involves the integration of DL1 (force feedback with visual display) and DL2 (tactile actuator with visual display). DL4 has been first implemented for a single digit (DL4a) and then for index finger and thumb (DL4b). To achieve DL4, the modified GRAB from DL1 has been further modified so that it can accommodate the tactile actuators (see Figure 2). This has involved replacement of each force transducer by a smaller device which fits within the tactile-actuator mechanism. These new force transducers have higher sensitivity than those used in DL1. In addition, the tactile actuator with a palmar mechanism from DL2 (i.e., a mechanism positioned in front of the finger pad) has been replaced in DL4 by a new design with a dorsal mechanism (i.e., a mechanism positioned behind the finger). This avoids interference from the mechanisms when the index finger and thumb are moved together, as required during manipulation of the virtual textiles. The sensitive pad of each digit rests on a force plate, which locates the moving contactors of the tactile actuator and transmits forces from the digit to the force transducer. Figure 3 shows the integrated system for DL4, with visual display and two-digit operation.

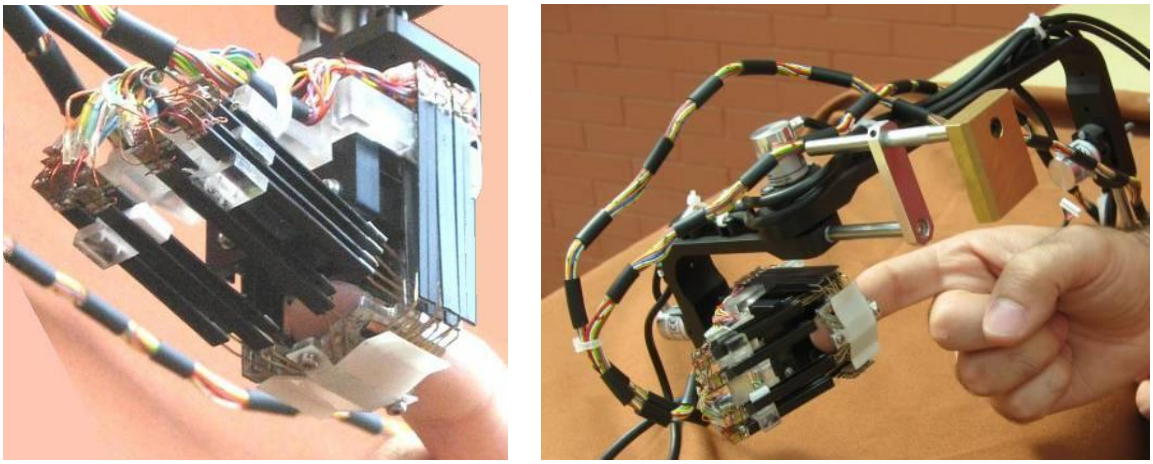


Figure 2. Development level DL4. The left panel shows the tactile actuator with dorsal mechanism, enclosing the force transducer (black box above the finger). The right panel shows the tactile actuator and force transducer mounted on the GRAB's instrumented gimbal.

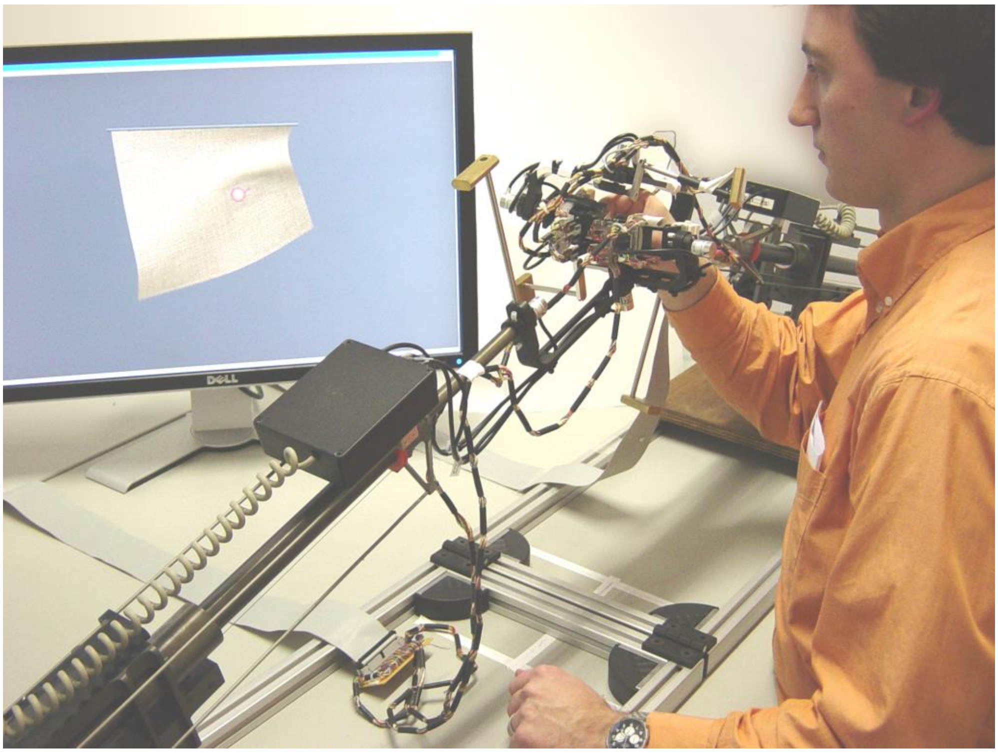


Figure 3. The integrated system for DL4. The visual display has been rotated for the photograph – it usually faces the user.

As mentioned in deliverable D5.1, two-digit operation at development level DL1 was satisfactory when the system represented a generic deformable object between thumb and finger. However, system instabilities were sometimes observed when the parameters of the virtual object were set to match those of a textile sample. This apparently relates to the effect of a relatively rigid virtual link between the two end effectors, such that small movements of one effector are associated with large changes of force at the other effector. Such instabilities became more of a problem in the subsequent development level DL4. However, the problem has been solved by running the software components which represent fingertip compliance in the dedicated processor which serves the

GRAB, rather than in the main processors which implement the virtual textile. (The GRAB processor offers a faster response time in the control loop.)

2.2. System validation for DL4

The various manipulation strategies which have been specified for the assessment of real and virtual textiles in the HAPTEX project are specified in Annex 1 (a revised version of D5.1, Annex 1). In a series of informal evaluations, it was established that the DL4 system offers the appropriate range of movements to support all of these manipulations. However, it is apparent that the performance of the interface has various non-ideal aspects, some of which result in significant limitations to the user:

- Of necessity, the tactile actuators involve some mechanism on the sensitive pads of the finger and thumb. This enforces a minimum spacing between the digits of 10 mm. In fact, when the virtual textile is held between the fingers with a small contact force, the (real) digit separation is 16 mm, with 6 mm separation between the thumb and finger mechanisms (falling to zero as the user applies increasing contact force – this is determined by the elastic element between the virtual contacts in the software model, stiffness 1250 N m^{-1}).
- The GRAB does not provide torques to support rotations of the hand, so the user must provide the torques required to overcome the rotational inertia and rotational resistance of the GRAB gimbal. It is difficult for the user to apply such torques because of the limited mechanical coupling between the user's hand and the end effectors of the GRAB. Consequently, the system works best with manipulations that maintain a relatively constant orientation of the fingers.
- As mentioned above, the spacing between the thumb and finger mechanisms falls from 6 mm to zero as the normal contact force is increased, according to a stiffness of 1250 N m^{-1}. In order to avoid collisions between the mechanisms (and allowing some safety margin), the user must not apply normal forces greater than approximately 5 N. This limit prevents the accurate simulation of some textile manipulations, since a normal force of 10 N or more may sometimes be used during manipulation of real textiles. (It is not possible to increase the virtual stiffness between the mechanisms because this creates instability in the force control loop.)
- The force feedback does not entirely compensate for drag and inertial forces in the GRAB mechanism – the user is often aware of forces associated with movement through the workspace, and in some cases the small forces from the virtual textile are masked.

2.3. System evaluation for DL4

In November 2007, the DL4 system was evaluated in Hannover. Virtual textiles (using software models derived from measurements on real textiles) were manipulated and their various properties were rated. These ratings were compared to those obtained in an equivalent assessment of the real textiles, and to physical data obtained using the Kawabata measurement system and other techniques.

The properties assessed (see Annex 1) were as follows:

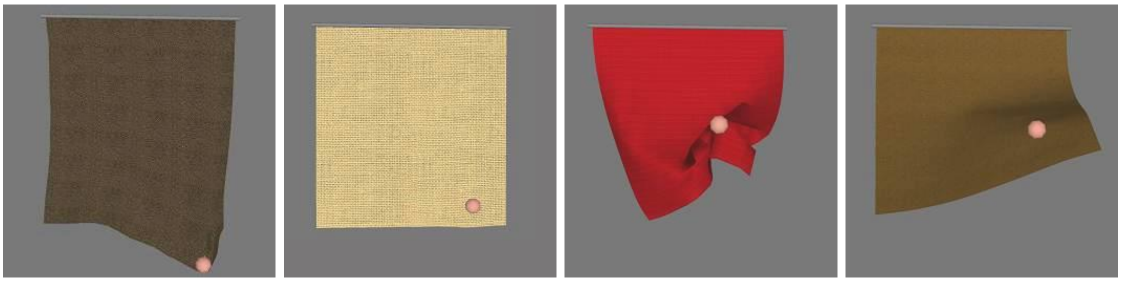
- tensile stiffness;
- surface roughness;
- surface friction;
- bending stiffness / weight / drapeability.

Two properties described in Annex 1 were not included in the assessment of the virtual textiles:

- shear stiffness;
- compressional stiffness.

(Technical problems with the GRAB – sticking of the mechanism during horizontal movements – meant that it was not possible to reliably perform the shear manipulation; compressional stiffness was not implemented in the software models.)

Each property was rated on a scale from 1 to 5, with reference examples provided to define each end of the range. Figure 4 shows screen shots for some of the manipulations.



tensile, reference "1" *tensile, reference "5"* *bending, reference "1"* *bending, reference "5"*

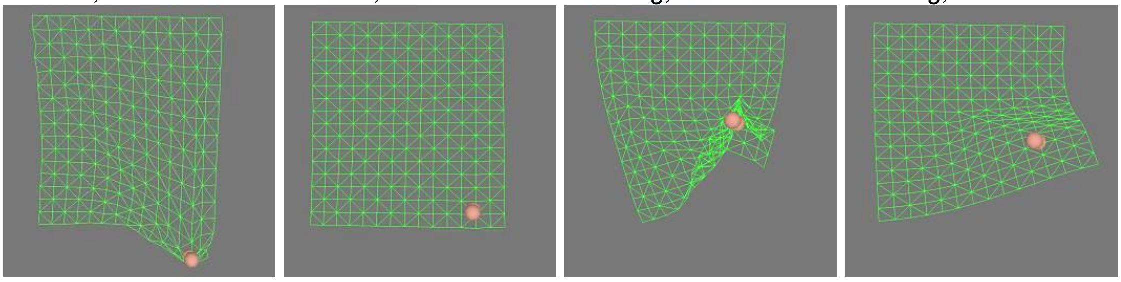


Figure 4. Screen shots for the tensile and bending manipulations of the associated reference textiles. The upper panels show visual rendering; the lower panels show the corresponding wire-frame view, as used in the evaluation.

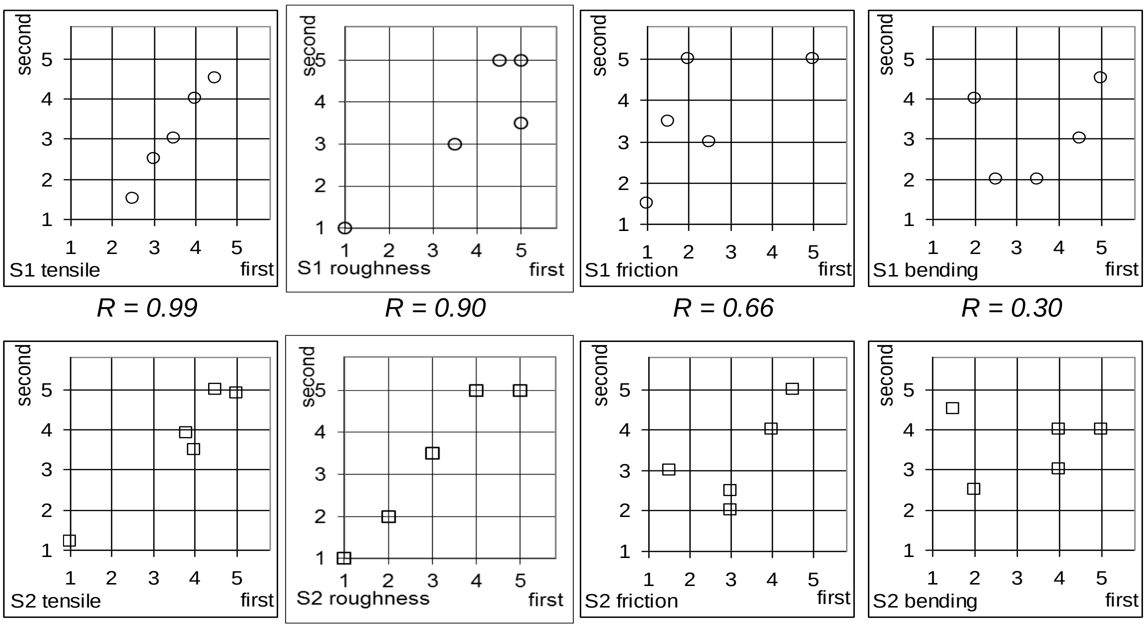
The procedures specified in Annex 1 were followed, with the following additions/modifications:

- Annex 1 specifies "with vision" and "without vision" conditions. However, manipulation of the virtual system without vision is difficult. As a compromise, a single test condition was used, with a "wire frame" representation of the virtual textiles.
- The bending and weight manipulations involve small forces which are difficult to detect in the virtual case (see above). Consequently a modified version of the assessment procedure for bending stiffness (Annex 1) was used, with the user raising a corner of the textile in the forward direction (see figure 4). The user was asked to make a visual assessment of bending stiffness – effectively an estimate of drape-ability, which includes the effect of both bending stiffness and weight.

- Two sets of five textiles were available. The first of these sets (“different fabrics”) was chosen for assessment. For each property, each textile was presented twice in a sequence of 10 items. Textiles were hung in the warp direction (weft direction for the tensile manipulation only).

2.4. Evaluation results for DL4

Data were obtained in Hannover from two users who have some familiarity with the DL4 system: S1 from UNEXE and S2 from UHAN. As mentioned above, each textile was assessed twice by each user. Figure 5 shows the relation between first and second assessments. It can be seen that, for both subjects, repeatability is good for assessment of tensile stiffness and surface roughness, and less good for assessment of surface friction and bending stiffness. The repeatability reflects the ease with which the user can make the assessment.

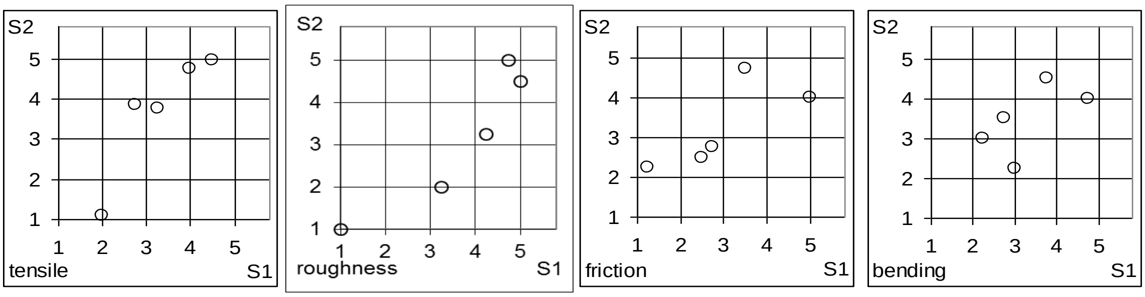


R = 0.99 *R = 0.90* *R = 0.66* *R = 0.30*

R = 0.97 *R = 0.97* *R = 0.67* *R = 0.07*

Figure 5. Relation of 1st and 2nd assessments for S1 (upper panels) and S2 (lower panels). The correlation coefficient R is also shown.

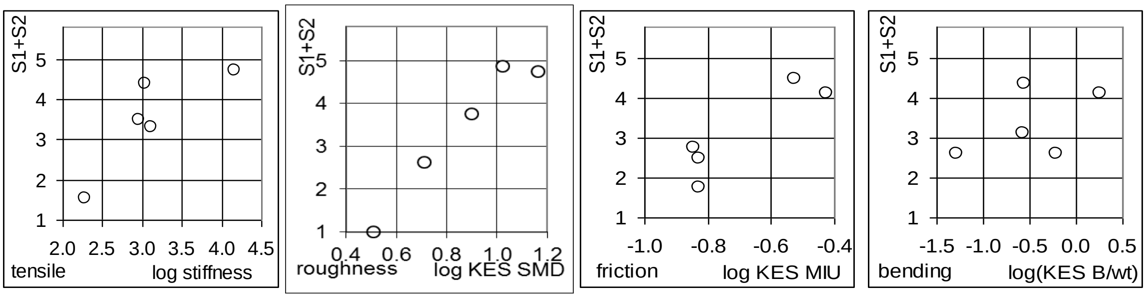
Figure 6 shows comparisons between mean ratings from S1 and S2. Again, the correspondence is good for assessment of tensile stiffness and surface roughness, and less good for assessment of surface friction and bending stiffness.



R = 0.91 *R = 0.93* *R = 0.76* *R = 0.61*

Figure 6. Comparisons between mean ratings from S1 and S2. The correlation coefficient R is also shown.

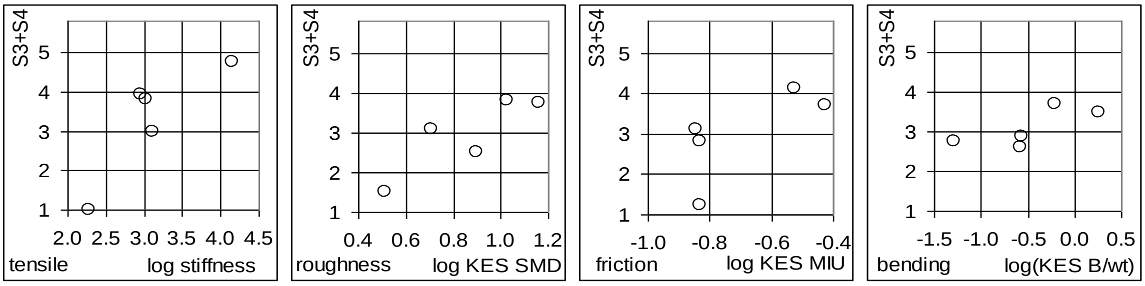
Figure 7 shows the relation between the subjective ratings (averaged over S1 and S2) and the corresponding physical values of tensile stiffness (measured at a force of 10 N), surface roughness, surface friction and bending/drapeability. (These are the values incorporated into the software models, derived from measurements on real textiles). The physical values are represented on logarithmic scales, in accordance with Weber's law. As mentioned above, the visual assessment of bending stiffness is effectively an assessment of drapeability – for this reason, the corresponding physical value was taken to be the ratio of bending stiffness to weight. For tensile stiffness, surface roughness and surface friction it can be seen that there is a good correspondence between the ratings of the virtual textiles and the physical parameters of the software models, This suggests that the DL4 system is delivering appropriate cues to the users, i.e., the virtual textiles are a good representation of the real textiles. As in the previous examples (Figures 4 and 5), the low correlation in the case of bending/drapeability reflects the difficulty of making the assessment.



R = 0.85 *R = 0.97* *R = 0.90* *R = 0.48*

Figure 7. Relation between subjective ratings of virtual textiles (mean of S1 and S2 data) and the corresponding physical values. The correlation coefficient R is also shown.

Corresponding data for the manipulation of real textiles were obtained in Tampere from two assessors: S3 from MIRALab (with experience in the fashion industry) and S4 (an expert from the textile industry, recruited by SWL). Figure 8 shows the relation between their subjective ratings (averaged over S3 and S4) and the corresponding physical values of tensile stiffness, surface roughness, surface friction and bending/drapeability (from measurements on the real textiles). It can be seen that there is quite good correspondence between the ratings of the real textiles and the measured physical parameters, in all four cases. According to the procedures in Annex 1, each real textile was assessed

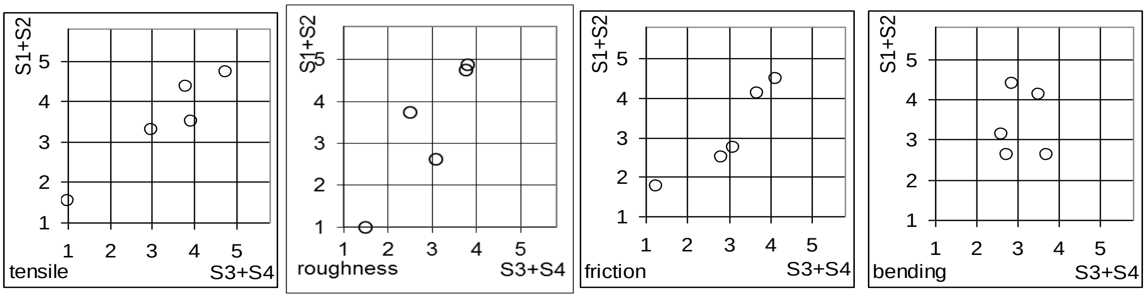


R = 0.85 *R = 0.86* *R = 0.70* *R = 0.74*

Figure 8. Relation between subjective ratings of real textiles (mean of S3 and S4 data) and the corresponding physical values. The correlation coefficient R is also shown.

in two conditions: “with vision” and “without vision”. The data presented here are for the “with vision” tensile and bending manipulations, and the “without vision” roughness and friction manipulations. (These conditions were chosen to be comparable with the wire-frame view used when assessing the virtual textiles.)

For overall evaluation of the DL4 system, perhaps the most informative comparison is between subjective ratings of virtual textiles and subjective ratings of the corresponding real textiles. This is shown in Figure 9. For tensile stiffness, surface roughness and surface friction it can be seen that there is a good correspondence between the ratings of the virtual textiles and the real textiles, providing further evidence that the virtual textiles are a good representation of the real textiles and that the DL4 system is delivering appropriate cues to the user.



R = 0.96 *R = 0.90* *R = 0.93* *R = 0.00*

Figure 9. Comparison between subjective ratings of virtual textiles (mean of S1 and S2 data) and the corresponding real textiles (mean of S3 and S4 data). The correlation coefficient R is also shown.

2.5. Evaluation of the tactile component

The tactile component of the DL4 system is one of the novel aspects of the HAPTEX project. We believe this to be the first time that distributed tactile stimulation has been combined with force feedback, using a tactile rendering strategy which is designed to reproduce the sensation of a real surface.

The tactile sensations produced by the DL4 system have multiple perceptual dimensions: spatial distribution (over the fingertip), overall intensity and spectral balance. However, in the assessment of surface properties described above, the user is asked to address only one of these dimensions – the “roughness” assessment is essentially based on only the intensity dimension of the perceived sensation. To obtain a true impression of the potential of the tactile component, it is necessary to look at the possibilities offered by the other perceptual dimensions. Unfortunately, due to time limitations it has only been possible to perform a preliminary study of this within the HAPTEX project – on the DL2 system, as described in deliverable D5.1.

In summary, the results from DL2 suggest that the intended perceptual dimensions (spatial distribution, overall intensity and spectral balance) are all available to test subjects. For uniform stimuli (i.e., stimuli with no spatial variation over the surface), the spectral dimension appears relatively weak – changes in spectral balance at constant subjective intensity tend to be less noticeable than changes in subjective intensity at constant spectral balance. (There are perhaps 4 to 5 discriminable steps of spectral balance along an equal-intensity contour.) There is a strong interaction between the perceived spatial aspects of the texture and the stimulation frequency. If the stimulation frequency is changed from 40 Hz to 320 Hz, the perceived sensation during active exploration changes much more if the texture is spatially non-uniform than if it is spatially uniform. It is clear that the spectral and spatial dimensions provide a significant enhancement to the available range of tactile sensations, i.e., overall intensity is not the only significant dimension.

3. Development level DL5

Development level DL5 is identical to DL4 (same software, same visual display, same design of tactile actuator with in-built force transducer), with the exception that the force-feedback component is a hand exoskeleton, replacing the GRAB system. The hand exoskeleton (see Figure 10) has been purpose-built for the HAPTEX project by PERCRO. It represents a significant advance and offers solutions to some of the problems of the DL4 system – particularly those relating to inertial and drag forces in the GRAB (see section 2.2). The new force-feedback system, with integrated force transducer and tactile actuator, will be demonstrated at the final project review as a proof of principle.

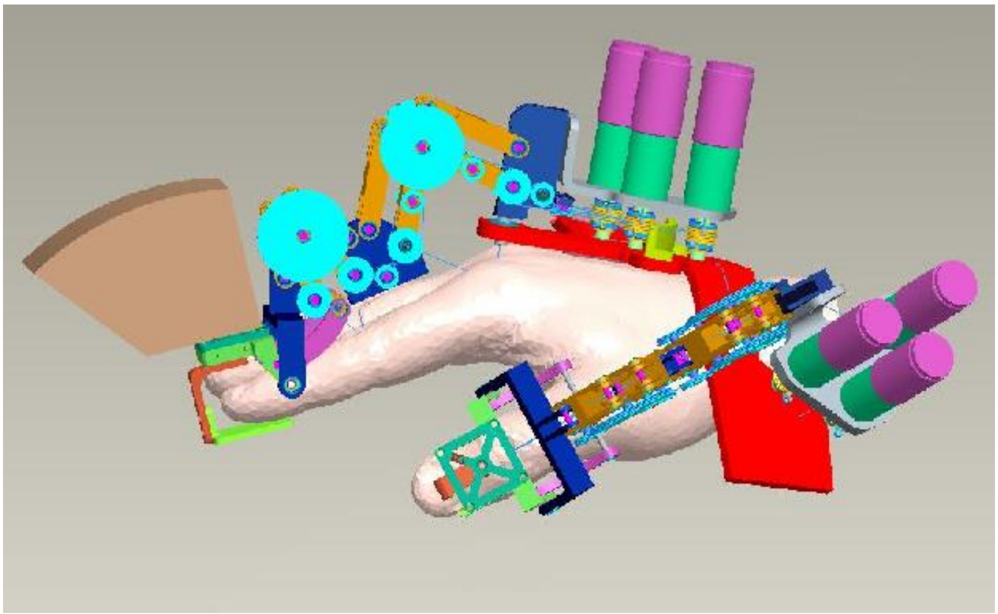


Figure 10. Layout of the hand exoskeleton. Forces are grounded with respect to the base plate (shown in red) whose position is measured by a mechanical tracking system.

4. Conclusion

The HAPTEX project has produced a workable system for the presentation of virtual textiles, with successful integration of a wide range of hardware and software components. As discussed above, experimental results show a good correspondence between assessments of the virtual textiles from the HAPTEX system (DL4) and assessments of the corresponding real textiles, providing evidence that the virtual system is delivering appropriate cues to the user. Ideally, a more extensive evaluation should be performed to confirm these findings and to fully investigate the potential of the HAPTEX system -- this is beyond the scope of the present project, due to time limitations.

The DL4 interface has various non-ideal aspects, some which result in significant limitations to the user – for example, the system is not always easy to navigate and some manipulatory movements are difficult. However, there is every reason to believe that such problems will be solved by future work (based on the DL5 system, for example). Building on the success of the HAPTEX project, the members of the HAPTEX consortium have plans for further projects to continue the development of virtual systems for textiles and other deformable objects, with the aid of national or international funding.

A happy user of the DL4 system at the HAPTEX workshop in Hannover, October 2007.

Annex 1. Subjective evaluation procedures

(Version November 10, 2007)

1. Samples

1.1 Fabric selection

Selection of five (5) different fabrics and five (5) similar fabrics from already measured samples (if possible) from the first, second and third set of fabrics.

1.2 Number and size of test specimen

One specimen or two parallel specimen per evaluator (depends on the availability of sample) are cut in one direction, size of 200 mm x 200 mm. Cut all specimen in same size and shape. Code the specimen and mark the length and width directions and the face and back sides of the samples but not by evaluator (labels may not be used). 1)

1.3 Conditioning

Condition the specimen for a minimum of 4 h at 20±2°C and 65±5% RH prior to evaluation if possible. Use the same conditions for evaluation if possible.1)

2. Evaluators

2.1 Selection of evaluators

Altogether five (5) evaluators (1 or two skilled and 2 or 3 semi-skilled) are selected e.g. from TUT Fibre materials Science and from textile and clothing industry or other appropriate area agreed between interested parties.

2.2 Preparation of evaluators

Evaluators wash their hands 0.5 h before the evaluation using the same washing procedure and hand soap (no moisturizers are allowed). Hands are dried with paper towels. Temperature changes and moisture are avoided after the hand washing. 1)

Evaluator should be free of distractions and relaxed. 1)

Evaluation may be performed seated or standing. 1)

Evaluator may not view the samples during the first evaluation round. Evaluator closes eyes using a blindfold. 1)

2.3 Facilitator

Facilitator gives relevant instructions for evaluation: evaluated properties, rating scale, number of samples, the order of procedure and duration of evaluation. 1)

Facilitator records the hand sensations given by the evaluator on a rating form. 1)

Facilitator turns and fixes the specimens for the evaluation of each direction and side.

Facilitator follows the position of the hand and the hold on the sample all along the evaluations.

A learning session before actual evaluation is recommended.

3. Procedure

3.1 Sample and reference fabrics holding

Sample holding is arranged according to scenario 3. The fabric is hanging from a stand, fixed at its upper edge (see figure 3.1) so that the size of workspace is 400 mm x 400 mm. The evaluator can rub and stretch the fabric. The evaluator can experience both force and tactile feedback.

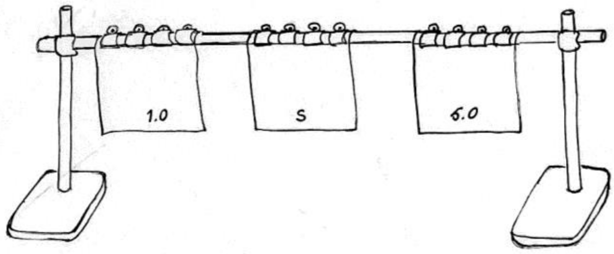


Figure 3.1 Sample (S) and reference fabrics (1.0, 5.0) holding arrangement (a sketch).

Place the reference fabrics on a stand - one on either side of the test fabric (reference fabric corresponding rate "1" on the left and reference fabric corresponding rate "5" on the right).

3.2 Subjective evaluation

Subjective evaluation of bending, shear, tensile, surface roughness and friction and compression is made using two fingers (thumb and forefinger). Front side of the fabric facing the tester; thumb on front side, finger on back side; concentrate on thumb to evaluate front side, concentrate on finger to evaluate back side; no rotation of the hand; no inversion of the fabric. Evaluate the sample separately in length and width directions and face and back sides when necessary. Rate each property of the sample. Use slow manipulation movements for all properties.

3.2.1 Bending

Grasp the free end of the sample at the side with thumb and forefinger. Lift the corner of the fabric forwards and allow it to bend around the finger. (Fig. 3.2) Bend the test piece first forwards and then backwards.

3.2.2 Shear

Grasp the sample close to the fixation with thumb and forefinger and shear the sample to the right and to the left. (Fig. 3.2)

3.2.3 Tensile

Grasp the free end of the sample at the side with thumb and forefinger. Pull the sample downwards and then let it return. Do not let the fabric loose from your fingers. (Fig. 3.2)

3.2.4 Surface roughness

Grasp halfway up sample with thumb and forefinger and slide your fingers downwards. (Fig. 3.2) [To slide your fingers upwards fix the free end of the sample with your other hand.]

3.2.5 Friction

Grasp the sample close to the fixation with thumb and forefinger and slide your fingers downwards. (Fig. 3.2) [To slide your fingers upwards fix the free end of the sample with your other hand.]

3.2.6 Compression

Grasp the sample with thumb and forefinger and compress your fingers together. (Fig. 3.2)

3.3 Rating scale and rating system

Select two reference fabrics for each property representing the end points of the rating scale. Compare the sample to the standard references. The same rates can be given to more than one sample if necessary. Use rating scale from 1.0 to 5.0 with intermediate points of 0.1 (i.e., 1.0, 1.1, 1.2 ....4.8, 4.9, 5.0) as follows:

3.3.1 Bending

1.0 = very weak resistance to bending, 5.0 = very strong resistance to bending
(take the average of forward and backward bending unless otherwise agreed)

3.3.2 Shear

1.0 = very weak resistance to shearing, 5.0 = very strong resistance to shearing

3.3.3 Tensile

1.0 = very weak resistance to stretching, 5.0 = very strong resistance to stretching

3.3.4 Surface roughness

1.0 = very smooth surface, 5.0 = very rough surface
(take the average of downward and upward roughness unless otherwise agreed)

3.3.5 Friction

1.0 = very slippery surface, 5.0 = very rough surface
(take the average of downward and upward friction unless otherwise agreed)

3.3.6 Compression

1.0 = very weak resistance to compressing, 5.0 = very strong resistance to compressing

3.4 Visual evaluation

3.4.1 Hand properties

Remove the blindfold. Repeat the evaluation procedures from 3.2.1 to 3.2.6 and rate the samples again for each property if agreed between interested parties.

3.4.2 Weight and drapeability

For evaluating weight push the fabric, halfway down the side edge, forwards with forefinger. Avoid fast movements, so that contact is continuous and the sensation of weight comes from the transition between "no weight" and "weight". Weight can be evaluated also non-visually if necessary.

Evaluate the weight as follows: 1.0=very light, 5.0=very heavy

For evaluating drapeability lift the corner of the fabric vertically, perhaps using a curved trajectory to ensure that the fabric folds towards the evaluator. (Fig. 3.2)

Evaluate the drapeability as follows: 1.0=very weak draping, 5.0= very strong draping

3.5 Second day evaluation

Repeat the both evaluation procedures on a second day again and rate the samples.

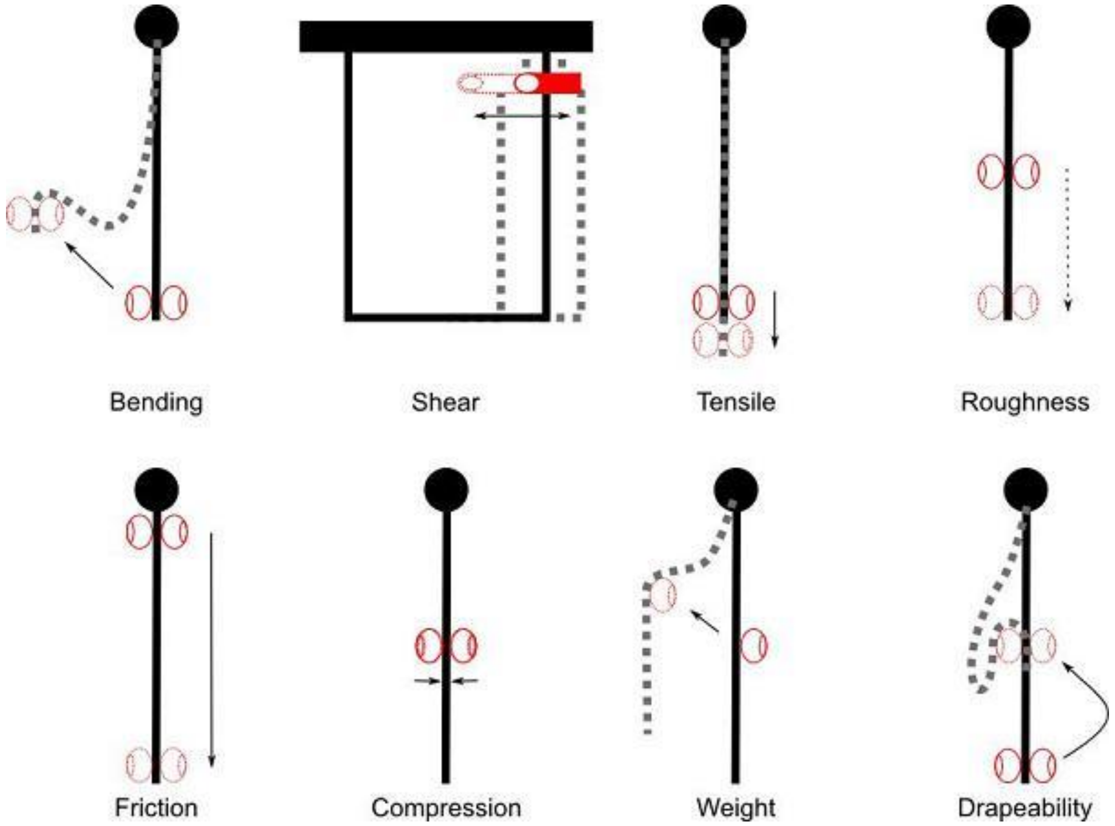


Figure 3.2 Finger positions and manipulation of each property.

4. Results

Compare the results between the evaluators. Compare the real-fabric results between the objective measurement results and between the virtual fabric results.

[1] Adapting the evaluation of AATCC Evaluation Procedure 5 (2001) (Fabric Hand: Guidelines for the subjective evaluation of AATCC Technical Manual/2002).