A touch rendering device in a virtual environment with kinesthetic and thermal feedback

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***Abstract*— This paper presents a haptic device that has been conceived to render both kinesthetic and thermal sensations computed from operator interaction with a 3D virtual environment. Computer simulation is based on a precise modeling algorithm of the thermal exchange between a bare finger and an object. The rendering is based on a closed loop control of both temperature and thermal flow signals. Each module composing the overall device and the rendering process are thoroughly described. We show that the whole system exhibits good technical performances in 3D multimodal interactive simulation.**

I. Introduction

In the field of virtual reality, haptic interaction remains difficult to render suitably, because haptics combines different sub-modalities: the kinesthetic part (force/motion), the tactile part (micro vibrations, texture), and the thermal part (heat/cold sensations). Major advances have been realized for kinesthetic rendering, but a lot is still to be done in the other parts.In this paper, we aimed to reach a further step by simulating the touching of smooth objects in a virtual environment with a high fidelity, whatever their position in space, their height, and the material they are made of. For that, it is necessary to have a device that is able to render both kinesthetic and thermal properties when touching virtual objects.

We designed a haptic display setup made of three elements:

- The tactile element, having two different functions:
  - A kinesthetic function: the device must be able to simulate the presence of an object surface wherever in the workspace. Thus, it must have a mobile stage that can be touched by the operator and that is free to move in the x, y, and z directions;
  - A thermal function: the device must be able to render the thermal sensations that are perceived for any touched material. Thus, it must be at the top of the kinesthetic stage, delivering hot and cold sensations.
- The tracking element: the position of the finger must be detected so that the mechanical stage can be moved accordingly and the thermal rendering process can be initiated accurately. Moreover, the device must be able to track, in real-time, the finger movement, and be in the neighborhood of the finger any time.
- A software element: a software must process the information that is provided by various sensors (finger position, thermal information); it must also drive the physical devices (mobile stage motors, temperature and flow of the thermal display interface) while managing the audio and the video components of the virtual environment. This software element requires real-time processing.

The following sections will describe the solution that has been developed for each component of this display.

II. Thermal rendering

A. Thermal rendering principles

The haptic sensations that are perceived during the touch of a smooth object, besides force, are mainly thermal. It allows us to recognize different objects materials (i.e. metal, insulator such as polystyrene...). However, thermal perception is significant mainly during the transient phase, i.e. at the very first seconds of touch, during which we have a strong thermal flow between the finger and the material. Afterwards, sensations decrease quickly, and a few tens of seconds after touch, finger is accustomed to the material. Here the thermal information is not meaningful anymore. This can be explained by the thermal flow evolution during touch, and highlights that only the first seconds of contact are pertinent. Therefore, many models [1] describing the thermal effects of contact, that are based on “steady state” models rather than “transient” ones are not suitable for our particular application: in these, real and modeled temperatures begin to converge only about 100 seconds after touch. This is obviously not applicable in this case. Other models that are more focused on the very first seconds of touch [2], are more suitable.

B. Real touch experiments

To estimate quantitatively the relevance of these models, it is necessary to measure the thermal flow evolution in real touch cases for various kinds of materials, with various thermal characteristics, ranging from very conductive (Aluminum) to very insulating (Polystyrene) materials. For this purpose, we embedded a temperature and flow sensor on the surface of the materials (see Fig. 1). These thermal and flow sensors[1] have a very low thermal resistance ($15.10^{-6} KW^{-1}m^2$) and, therefore, have a limited impact on the thermal flow measures.

The contact pressure between the finger and the material plays an important role in the contact thermal resistance and

[1]CAPTEC, France

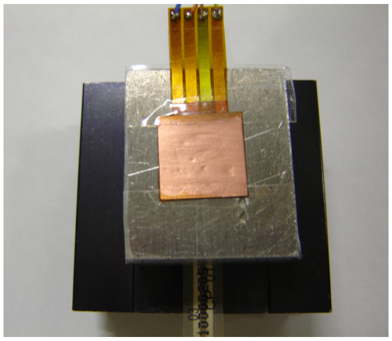

Fig. 1. Real experiments setup

the contact surface, which modifies the measured thermal flow. Therefore, tests were led by trained people at the same contact pressure, which was measured with a FSR pressure sensor placed under the material. Results are shown on Fig. 2.

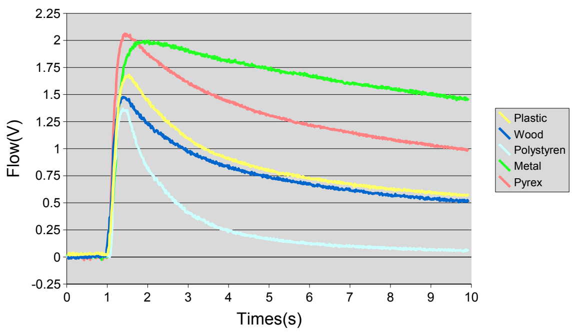

Fig. 2. Real experiments flow evolution (beginning at t=1s)

In each case, flow increases quickly at first, then decreases at various rates. The more insulating the materials are, the faster the flow decreases, due to quicker material surface heating. During the first step, sensations inform mainly about the object temperature. During the second step, they inform mainly about the object constitutive material. We checked that the sensor interfered little in the measurements, by adding a second sensor on the first one.

The only change during the touch of two different materials is the flow between finger and material, and the surface contact temperature of the finger, which is completely correlated to the flow. Thus, the aim of the thermal rendering module is to replicate the curves of Fig. 2, in order to render realistic sensations.

C. Thermal rendering based on pure analytical models

To have any kind of flow, a device that can produce positive and negative flow is necessary. Such a device is called a Peltier thermoelectric module (TEM) whose thermal flows are controlled by electric currents, which is the *de facto* standard for generating heat and cold. It is interfaced with a computer through an input/output PC card and a custom made electronic card. The model developed in [2], is one of the most advanced analytical models and is based on the following assumptions:

- Finger and material contact can be modeled by one dimension transient heat transfer equations.
- Thermal contact resistance is negligible.
- Material is semi-infinite with an initial constant homogeneous temperature in the whole material (T_1).
- Finger is made of a single material (epidermis) which is semi-infinite. The role of blood perfusion is negligible; initial temperature is constant and homogeneous in the whole finger (T_2), it is the finger surface temperature.

These approximations cannot be accurate enough when a steady state is reached. Indeed, blood perfusion and finger structure play a major role. But it is perhaps sufficient in the transient phase (few seconds) during which pertinent sensations are perceived. With these approximations, an analytical expression for the contact temperature between the material and the finger can be written:

$$T_{\text{contact}} = \frac{\beta_m T_{m_{\text{init}}} + \beta_s T_{s_{\text{init}}}}{\beta_m + \beta_s} \tag{1}$$

where $\beta = \sqrt{k\rho c}$, k the thermal conductivity ($Wm^{-1}K^{-1}$), ρ the density (kgm^{-3}), c the specific heat ($Jkg^{-1}K^{-1}$)) of the material or skin. The letter s is used for the skin and m for the contact material. $T(x,t)$ is the temperature in the material at location x and time t. The thermal flow between the two objects $j = -k\frac{\partial T}{\partial x}$ (Wm^{-2})) can be written as follows:

$$j_{\text{contact}} = \frac{k_s(T_{\text{contact}} - T_{s_{\text{init}}})}{\sqrt{\pi \alpha_s t}} \tag{2}$$

where $\alpha = \frac{k}{\rho c}$. Thus, thermal flow only depends on the following terms: skin thermal characteristics, and T_{contact}. In this case, it would be possible to simulate every material with the TEM by setting its initial temperature T_p as follows:

$$T_p = \left(\frac{\beta_m T_{m_{\text{init}}} + \beta_s T_{s_{\text{init}}}}{\beta_m + \beta_s}\right)\left(\frac{\beta_p + \beta_s}{\beta_p}\right) - \frac{\beta_s T_{s_{\text{init}}}}{\beta_p} \tag{3}$$

where the letter p is used for the TEM module. This shows that by changing TEM temperatures from the lowest to the highest, every kind of flow evolution curves possible for every existing material at every temperature could be obtained. To validate this model, we measured the flow between the finger and the TEM, with a flow sensor fixed above the TEM, as a function of time, for a large spectrum of T_p. This experiment yielded the results in Fig.3.

There is a large difference between these curves. However, the differences are related to their amplitudes, not their shape. Unfortunately, these curves do not correspond exactly to the real measurement curves for all kinds of materials. Their shapes look mostly like conductive ones (slow flow decreasing): this is due to the conductive ceramic material at the top of the TEM. The same observations have been done with subjective touch: sensations were different from real materials sensations. This shows that a control based on pure analytical models is too approximate for our purpose: it is not exactly the same to have various materials at ambient temperature, and a single material at various temperatures.

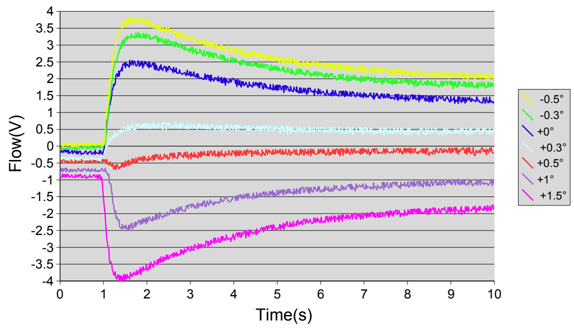

Fig. 3. TEM flow evolution. Temperatures are relative to ambient air

While the first second of touch can be approximated by this model, this is not the case after. A closed-loop thermal flow control is then necessary.

D. Thermal rendering based on closed-loop thermal flow control

Since the exact thermal flow to reach is known (Fig. 2) through flow sensors, it can be replayed at a later time through closed-loop control of the TEM. However, since thermal phenomenons have generally slow dynamics, the swiftness of the TEM is crucial in this case. The current step response of the TEM has been measured by a flow sensor (that is fixed above the TEM). Results are shown in Fig. 4.

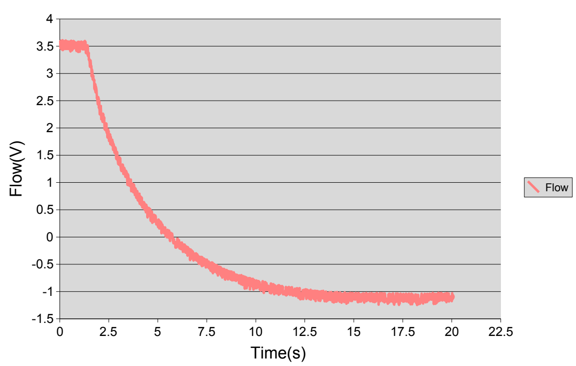

Fig. 4. Step response from a TEM

It is quite evident that the TEM has a large thermal inertia. Response time is too large to enable a direct control of the TEM with a simple closed-loop control, due to the sudden contact flow. This is why, we chose to give the TEM a temperature that corresponds to equation 3, so that the initial rendered thermal flow is similar to the real one. After that, the closed-loop control of the TEM is used to correct the gap between the real response curve and the measured one. This gap is not too high in this case and can be predicted, so that such a closed-loop control is feasible. Our results are shown in figures 5, 6, and 7.

Flow values that are obtained with this method (analytical model corrected by a closed-loop control) are far better than with a single analytical model, and are quite close to the real measures, even for polystyrene, which thermal characteristics are very different from TEM ones.

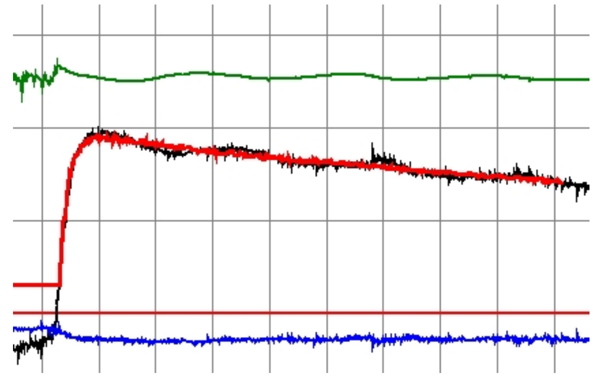

Fig. 5. Flow tracking of metal (in red:desired, in black:obtained, in green:current control)

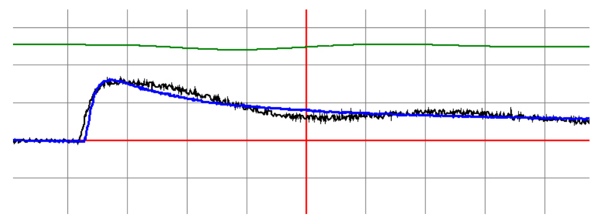

Fig. 6. Flow tracking of wood (in blue:desired, in black:obtained, in green:current control)

Since the response is quite satisfying, this control method to render the thermal sensations in our device is adopted. The problem with this method, though, is that a real measurement of the flow with the real material must be done before simulating it. It might be limiting to have to find a sample before being able to render it. Moreover, a larger problem arises: the response flow is modified by a change in the temperatures of the material and/or of the finger surface. This restricts strongly the utility of this control method. Thus, to improve its scope, an efficient predictive model, that avoids the need to make real measurements and allows a better use of the TEM, is to be found.

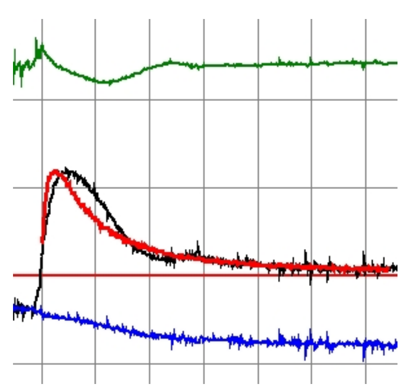

Fig. 7. Flow tracking of polystyrene (in red:desired, in black:obtained, in green:current control)

E. Finite-element based simulation model

Since there is no pure analytical model of the contact that can fulfill the aim here, finite-element calculations allow the best possible simulation in our case. The reason why the classical contact analytical model did not work completely well is probably related to the complex structure of the finger and the thermal resistance between the finger and the material, and perhaps, due partly to the presence of the flow sensor. To be taken into account is also the blood flow inside the finger, which is responsible for warming the material. Thus, the whole contact system was modeled as shown on Fig. 8.

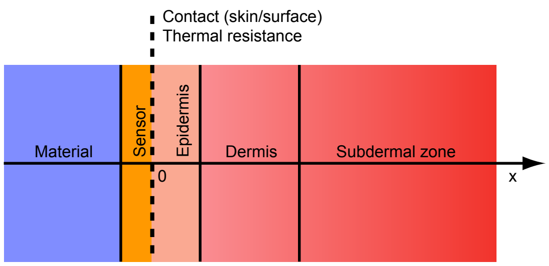

Fig. 8. Contact system

The basic physical equations used here are based on the energy conservation in open systems:

$$\rho c \frac{\partial T}{\partial t} = -\frac{\partial j}{\partial x} + \dot{m} c_b (T_{ar} - T) \quad (4)$$

The second term in this equation is the heat production term [3], that is, approximately, only due to heat exchange between blood and skin, where $\dot{m}$ is the blood flow rate per unit volume, c_b the specific heat of blood and T_{ar} the arterial blood temperature. With this equation, it is possible to write suitable equations for each node in the finite-element method, e.g.:

$$T_m^{p+1} = T_m^p(1 - 2F_i - H_i) + F_i(T_{m+1}^p + T_{m-1}^p) + T_{ar}H_i \quad (5)$$

for a node with blood perfusion, where T_m^p is the temperature of node m at time increment number p, F_i and H_i are constants depending on thermal characteristics of the skin location, on time increment, and on step increment between nodes. Another equation can be obtained:

$$T_m^{p+1} = T_m^p(1 - G_{ij}(k_i + k_j)) + G_{ij}(k_i T_{m-1}^p + k_j T_{m+1}^p) \quad (6)$$

for the frontier node between material and sensor (no blood perfusion), where G_{ij} is a constant depending on thermal characteristics of material and sensor, on time increment, and on step increment between nodes. Similar equations can be obtained for all the other nodes. However, the contact node between sensor and finger needs to be treated with particular caution, because there is large temperature and flow discontinuities at this node at the beginning of the touch. A classical finite-element calculation here would lead to very false results, which would converge to real ones, but only a few seconds after the beginning of the touch. This is not acceptable for such a simulation. To treat this particular difficulty, a semi-analytical method is used:

When thermal resistance is negligible (case A), it can be written [4], in the particular case of two homogeneous semi-infinite materials 1 and 2 which have constant initial temperatures T_1 and T_2, which are set in contact at $t = 0$:

$$T(x,t) = (T_{\text{init}} - T_{s_0})\,\text{erf}\left(\frac{x}{2\sqrt{\alpha t}}\right) + T_{\text{contact}} \quad (7)$$

where T_{contact}, β and α have the same meanings as in equations 1, 2, and 3.

When thermal resistance R_{th} is not negligible (case B), there is a thermal flow at contact:

$$j_{\text{contact}} = \frac{T_{\text{skin}} - T_{\text{sensor}}}{R_{th}}. \quad (8)$$

In the particular case of a homogeneous semi-infinite material with a constant initial temperature T and with a constant thermal flow j at one bounder after time $t = 0$ the following equation holds:

$$T(x,t) = T_{\text{init}} + \frac{2 j_{\text{contact}} \sqrt{\frac{\alpha t}{\pi}}}{k} e^{\frac{-x^2}{4\alpha t}} - \frac{j_1 x}{k}\,\text{erfc}\left(\frac{x}{2\sqrt{\alpha t}}\right) \quad (9)$$

Thus, in both cases A and B, we can see that in the particular case of a homogeneous semi-infinite material with a constant initial temperature T an analytical expression of T can be used. It is not the case for us, but our problem can always be separated into two different problems, thanks to the superposition property of thermal systems. The overall T can be decomposed into $T_1 + T_2$ and overall j_{contact} into $j_{\text{contact1}} + j_{\text{contact2}}$, choosing T_1 and j_{contact1} solvable analytically; and T_2 and j_{contact2} remaining temperatures and flows which, since they are small, are solvable by pure finite-element methods. An example is given below for the case B of not negligible contact thermal resistance.

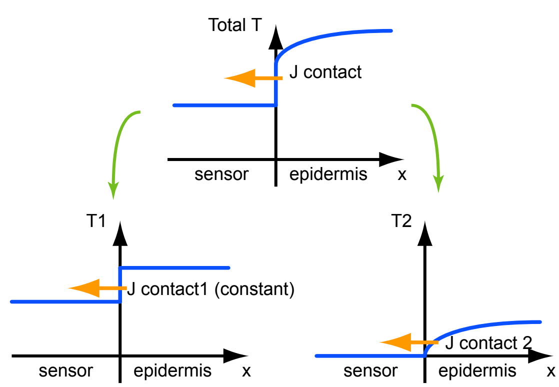

Fig. 9. Decomposition example

Problem 1 has an analytical result. Problem 2 has a simple finite-element result. Thus, for each iteration, the complete temperature results can be found, and j_{contact2} deduced from:

$$j_{\text{contact2}} = \frac{T_{2_{\text{SkinContact}}} - T_{2_{\text{SensorContact}}}}{R_{th}} - j_{\text{contact1}} \quad (10)$$

j_{contact2} is used for the next iteration of the simulation. Thermal flows can be then computed from temperatures by derivation. Fig. 10 shows a diagram giving the working principle of the simulation software.

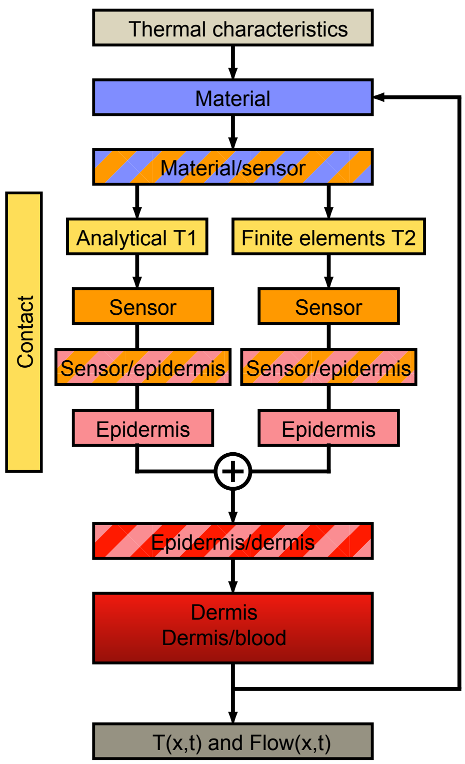

Fig. 10. Simulation principle

As input, this program needs the thermal characteristics and a 1D size of the materials and skin parts, the material initial temperature, and the external skin temperature (that is measured with an IR temperature sensor). We simulated the same materials as our available samples. The following values were taken from the literature:

- Aluminium: $k = 200$, $c = 900$, $\rho = 2750$;
- Pyrex: $k = 1.4$, $c = 835$, $\rho = 2225$;
- Wood: $k = 0.11$, $c = 415$, $\rho = 2720$;
- Polystyrene: $k = 0.027$, $c = 1210$, $\rho = 55$;
- Sensor: $k = 2.5$, $c = 385$, $\rho = 8933$;
- Skin epidermis: $k = 0.34$, $c = 3340$, $\rho = 1200$ with a width of $0.7mm$.

The simulated flows are shown in figure 11.

This model is able to simulate the thermal response of materials with a good accuracy. The tiny differences between model and reality are probably mostly related to differences between real thermal characteristics such as conductivity and thermal contact resistance, and the corresponding values that were taken from the literature. Thus, this model makes it possible to reproduce any thermal situation without having to make real measurements in the same conditions.

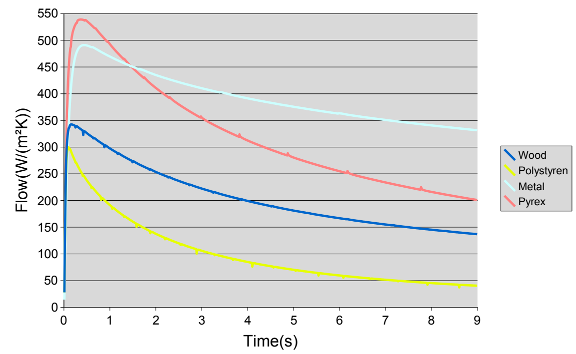

Fig. 11. Simulated flows obtained with our method

This predictive model, with the closed-loop rendering method that was detailed above are the core of the thermal element of the device.

III. Kinesthetic interface

The kinesthetic interface is responsible for the rendering of contact forces. Since the thermal module must be placed under the finger, a XYZ positioning device is also required. Such a haptic device has been conceived in our laboratory [5].

A. XYZ positioning table

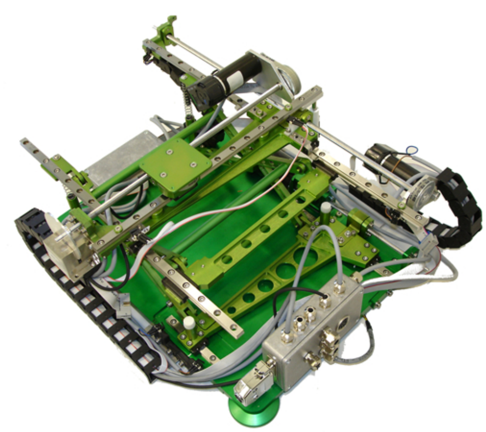

Fig. 12. The XYZ table

As shown in the Fig. 12, the kinesthetic interface prototype is made as a compact XYZ Cartesian device. The leitmotiv of the device had been lowest friction, computer notebook size, and speed, to allow real-time force display.

B. Haptic arm

In order to be able to track the finger movement, a convenient solution was to attach it to a Phantom Omni[2] haptic device because of the use of the I-Touch framework for the software part, which already includes full support for such a device. The finger was simply attached to this device, allowing its tip to touch the thermal interface.

[2]Phantom Omni is sold by Sensable, USA

IV. THE I-TOUCH FRAMEWORK

The I-Touch framework [6] [7] has been devised in order to simplify the producing of haptic software solution in the academic domain. Its aim is to reduce significantly the implementation time starting from a haptic idea to its actual testing and evaluation . For this, it features a support for many haptic devices, and more can be added easily. For example, support of the XYZ table has been specifically added for this experiment; however its integration from scratch did not take more than two days. Moreover, the framework is completely customizable, allowing the production of a new scenario efficiently. XML configuration and serialization is of great help toward this objective. Furthermore, a full multi-modal rendering engine is available inside the framework. It was the logical choice for our experiments, since most of the functionalities were already inside it.

We integrated two new devices: the XYZ table, which has been devised as a new six degrees of freedom device, with rotations blocked, and the thermal device, which required special developments. The offline calculations of materials are for now done outside I-Touch, however we hope to integrate them in the near future. The integration of the different components into I-Touch was straightforward, producing the results discussed in the next section.

V. RESULTS

After integrating all these components, and interfacing them with I-Touch, we tested the performances of the overall rendering system. The four materials that appear in the virtual environments were simulated off-line before the beginning of the rendering. The preliminary cooling of the materials, measured through the temperature sensor of the flow sensor, was done in accordance with formula 3. Depending on the position of the finger, different thermal characteristics are used. For this reason, the finger should not switch too fast between two different materials, so that the TEM has time to adapt to the adequate temperature. The thermal rendering is triggered when contact is detected in I-Touch. The finger is attached to the haptic arm with adhesive. At the beginning of the simulation, a calibration step is done, so that the XYZ table is always just below the finger and tracks it with a simple closed loop control.

A presentation of the device elements and a demonstration of a thermal rendering session of the device can be found on the following URL: `www.i-touch.org/thermal/`

The technical performances of the kinesthetic setup are very good, with accurate positions of the objects. Of course, the tracking of the thermal rendering from object to finger was of crucial importance, but the responsiveness of the XYZ table and I-Touch were largely enough to have a real-time tracking. Performances of the thermal rendering have been subjectively judged fair. Most materials could be detected, with relatively good "cold" and "hot" sensations, as for real materials, even if there was often confusion between wood and plastic - like in real life, if tactile feedback is removed. However, psychophysical blind tests on a panel of operators have still to be led to demonstrate how realistic the device is judged by untrained people.

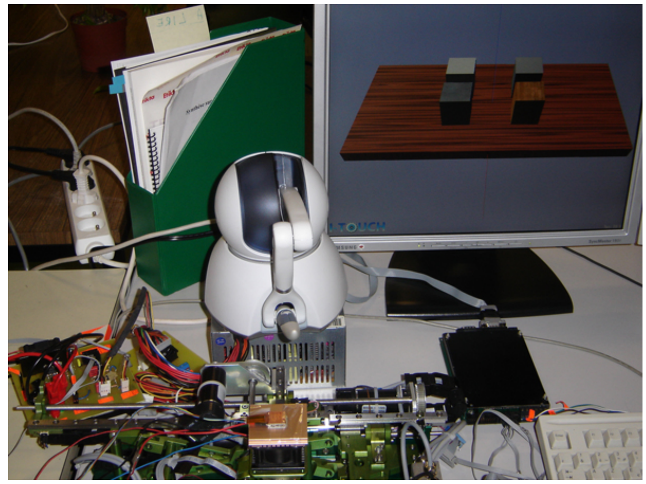

Fig. 13. Our experimental setup

VI. CONCLUSION

A combined kinesthetic and thermal rendering device is proposed in order to simulate flat and smooth surfaces of objects with different properties in virtual reality. A Cartesian haptic display (μ-haptic) has been used, as well as a haptic framework software I-Touch. An accurate thermal simulation of the transient contact phase is necessary. We developed a thermal simulating model based on finite-elements, which was used with a closed-loop thermal flow control method to render thermal sensations, based on a TEM and a flow sensor. Demonstration of the device performances have been done, with satisfying preliminary results in terms of mechanical and thermal flow rendering behaviors. We will strive in further works to improve the closed-loop control method to reduce the oscillations of the response for very insulating materials, and to lead psychophysical tests to assess its perceptual performances on operators. We aim at creating a full featured solution for kinesthetic/thermal rendering in interactive virtual simulation.

REFERENCES

[1] M. Benali-Khoudja, M. Hafez, J.-M. Alexandre, J. Benachour, and A. Kheddar, "Thermal feedback model for virtual reality," *MHS*, 2003.

[2] A. Yamamoto, B. Cros, H. Hashimoto, and T. Higuch, "Control of thermal tactile display based on prediction of contact temperature," *ICRA*, 2004.

[3] D. Hodson, J. Barbenel, and G. Eason, "Modeling transient heat transfer through the skin and a contact material," *Phys. Med. Biol.*, 1989.

[4] F. Incropera and D. DeWitt, *Fundamentals of Heat and Mass Transfer*. John Wiley and Sons Ed, 1996.

[5] A. Drif, A. Ali, N. Séguy, and A. Kheddar, "The μ-haptic, an inclusive haptic interface," *IEEE International Conference on Mechatronics and Automation, Niagara Falls, Ontario*, 2005.

[6] A. Pocheville, A. Kheddar, and K. Yokoi, "I-touch: A generic multimodal framework for industry virtual prototyping," *TeXCRA*, 2004.

[7] A. Pocheville and A. Kheddar, "I-touch: a framework for computer haptics," *IROS Workshop*, 2005.