TECHNICAL SPECIFICATION

ISO/IEC TS 23884

First edition
2021-12

Information technology — Computer graphics, image processing and environmental data representation — Material property and parameter representation for model-based haptic simulation of objects in virtual, mixed and augmented reality (VR/MAR)

Technologies de l'information — Infographie, traitement d'images et représentation des données environnementales — Propriété matérielle et représentation des paramètres pour la simulation haptique basée sur un modèle d'objets en réalité virtuelle, mixte et augmentée

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Foreword

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This document was prepared by Joint Technical Committee ISO/IEC JTC 1, *Information technology*, Subcommittee SC 24, *Computer graphics, image processing and environmental data representation*.

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Introduction

Both virtual reality (VR) and mixed and augmented reality (MAR) employ virtual, synthetic and computer-generated objects in their respective scenes, and they are rendered not only visually but in other modalities in order to provide rich user experience based on realism, presence and augmentation.

VR and MAR applications are increasingly using haptic feedback to allow the user to interact physically with the virtual or real objects and provide higher realism and elevated experience. That is, the input from and output to the user may be delivered kinaesthetically (i.e. force feedback) through physical simulation and the resulting force rendered through mechanical haptic devices. Note that the interacting virtual or real object may be situated in virtual reality (VR), augmented reality (AR) and augmented virtuality (AVR) – namely, across all types of MAR.

A correct and effective rendering of forces requires the relevant physical description of the materials of the objects involved in the physical interaction and simulation. In addition, depending on the needs of the application, different haptic rendering algorithms may be employed. Conventional standards for virtual and mixed reality have lacked constructs for expressing such material properties or algorithmic details and thereby supporting a comprehensive, faithful and flexible haptic rendering. For example, most current standard 3D graphic or virtual object representations can only describe material properties for visual rendering (e.g. for lighting effects and shading).

This document also provides definitions for terms related to material properties and physical simulation in the context of the haptic rendering and its algorithms.

The target audience of this document are mainly VR and MAR system developers and content designers interested in specifying and using haptic interaction. This document provides a basis for application standards for any VR and MAR applications and content representation that uses haptic modality for input and output.

However, this document establishes the information model. It does not promote or propose to use a specific language, file format, algorithm, device, implementation method or standard. The model is intended to be considered as the minimal basic model that can be extended for other purposes in actual implementation.

The content of this document is derived from ISO/IEC 18039, which, among other things, specifies the possible inclusion of haptic feedback (and associated devices) in experiential VR and MAR contents (and systems). The specification can be one important component in ISO/IEC 3721-1[1]), whose purpose is to lay out and specify the information model for various essential MAR content components and their relationships. While ISO/IEC 3721-1 lays the foundation and overall framework, it does not go into all the details (e.g. material or haptic properties of an object). As haptic feedback may be used in purely virtual environments as well, this document also relates to ISO/IEC 19775-1.

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1)   Under preparation. Stage at the time of publication: ISO/IEC DIS 3721-1:2021.

Information technology — Computer graphics, image processing and environmental data representation — Material property and parameter representation for model-based haptic simulation of objects in virtual, mixed and augmented reality (VR/MAR)

1 Scope

This document specifies:

— physical and material parameters of virtual or real objects expressed to support comprehensive haptic rendering methods, such as stiffness, friction and micro-textures;

— a flexible specification of the haptic rendering algorithm itself.

It supplements other standards that describe scene or content description and information models for virtual and mixed reality, such as ISO/IEC 19775 and ISO/IEC 3721-1.

2 Normative references

There are no normative references in this document.

3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1.1
dynamic friction
friction that changes dynamically under certain external conditions

3.1.2
friction
tangential force emanating from the contact between two objects

3.1.3
haptic
kinaesthetic, force feedback and tactile feedback

3.1.4
haptic device
apparatus that delivers computer-simulated forces and torque to a human user for sensation, and also receives input in the form of force and torque to be conveyed to the computer simulation of virtual and mixed reality environment for emulating physical interaction

1

3.1.5
haptic modality
modality synonymous to the haptic sensation

3.1.6
haptic rendering
computing the amount of forces and torques occurring at the interaction point, based on the physical simulation and interaction of the virtual and mixed reality world, and reflecting them to the user through the haptic device

3.1.7
physical interaction
interaction, real or virtual, between a user and object(s) that involves the use of forces and torques via contact

3.1.8
physical simulation
simulating the dynamic physical phenomena in the virtual and mixed reality environment based on the environment description and given physical laws, and in the process, computing the relevant parameter values, such as the amount of forces and torques

3.1.9
stiffness
rigidity of an object and the extent to which the object resists deformation in response to an applied force

3.1.10
surface texture
micro surface texture
micro-scaled protrusion pattern on the surface of an object

3.2 Abbreviated terms

AR   augmented reality

FFT   fast Fourier transform

MAR   mixed and augmented reality

VR   virtual reality

4 Overview: Material properties for haptic simulation

4.1 General

Haptic rendering in the context of VR or MAR simulation refers to computing for the proper force or torque to be exerted by the haptic device at a given point in the VR or MAR space (e.g. magnitude and direction), see Figure 1.
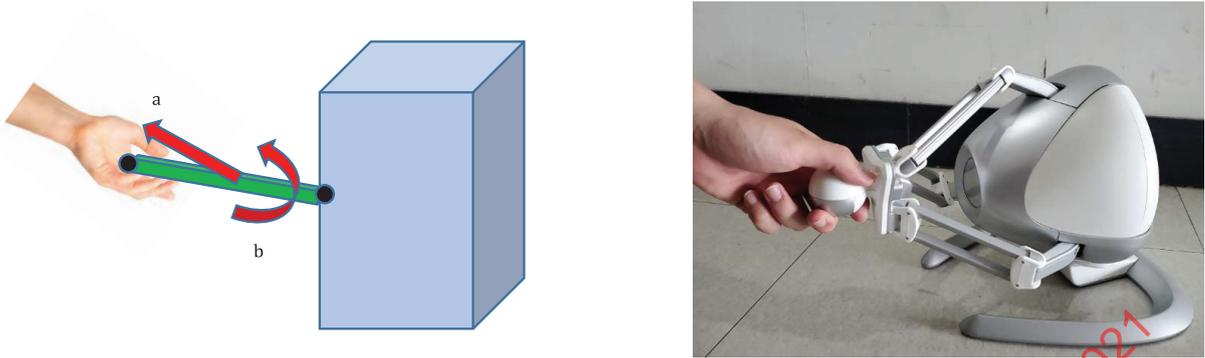
^a Force.

^b Torque.

Figure 1 — Physical interaction with a virtual or real object (left) and using the haptic device to obtain kinaesthetic feedback (right)

H3D API is an open-source, cross-platform, scene graph AI that has extended the X3D material and surface node[3] as "SmoothSurface," "FrictionalSurface," "DepthMapSurface" and "HapticTextureMap" to express various haptic parameters directly.

For example, the declaration:

<SmoothSurface stiffness="1,0" damping="0,5"/>

includes the linear stiffness of 1,0 and the damping factor of 0,5 for computing the resulting force as in Formula (1):

$$F = kx + vx'$$ (1)

where

x is the object displacement;

k is the stiffness factor;

v is the damping factor.

The following declaration is used for representing a "frictional" surface with added parameters such as the static and dynamic friction constants. Consequently, the resulting force is computed differently from Formula (1) with these added parameters.

<FrictionalSurface stiffness="1,0" damping="0,5" staticFriction="0,61" dynamicFriction="0,4"/>

This approach is simple and effective, and can be used as a quick fix for the absence of any haptic material properties to begin within X3D or other similar simulation content representation. But it is also ad hoc in that different types of surfaces are defined with the surface-specific parameter sets. This in turn makes the flexible specification of the haptic rendering algorithm difficult. Haptic rendering is associated with the physical simulation of virtual or real objects which can be carried out at different degrees of accuracy and complexity, and also the mechanical characteristics of the haptic device used and the available computing resource. This makes the haptic rendering to employ a particular model or algorithm. At any rate, usual physical simulation generally computes for the gross amount of forces and torques arising at object contact points and moments. The most basic physical simulation and haptic output requires various parameters, the three basic ones being i) stiffness, ii) friction and iii) surface texture information, which are all material properties of the interacting objects.

4.2 Stiffness

Stiffness (see Figure 2) refers to the rigidity of an object. It describes the extent to which the object resists deformation in response to an applied force. In haptic rendering, stiffness should ideally be given differently at the surfaces or vertices of the object. In large and slow deformation, stiffness may be non-constant. Stiffness is measured in newtons per meter.
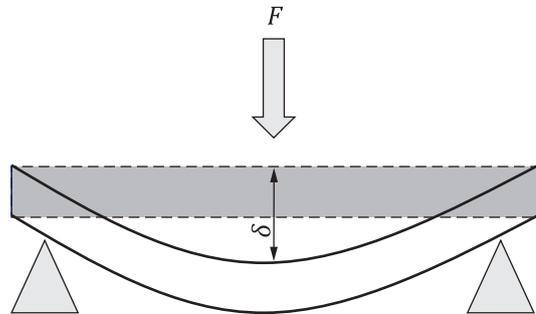

Figure 2 — An object deformed by δ from external force, F

Stiffness may be computed from other related object or material parameters, especially to model its time-dependent dynamics. For instance, Formula (2) shows the non-linear Hunt-Crossley model equation[4] that describes the elastic object deformation (i.e. x represents the object or surface displacement) and associated force (f) using three parameters: K (spring constant), B (damping coefficient) and m (object- or material-specific constant that is typically between 1 and 2). The three parameters in essence indirectly represent the object or material stiffness (ε is an arbitrary error term).

$$f = Kx^m(t) + Bx^m(t) + x'(t) + \varepsilon \tag{2}$$

where

f is the associated force;

K is the spring constant;

x is the object or surface displacement;

m is the object- or material-specific constant;

B is the damping coefficient;

ε is an arbitrary error term.

4.3 Friction

Friction refers to the tangential force emanating from the contact between two objects and responsible for producing high-frequency contact response. It is the source of the force that resists the relative motion of two objects in contact (see Figure 3).
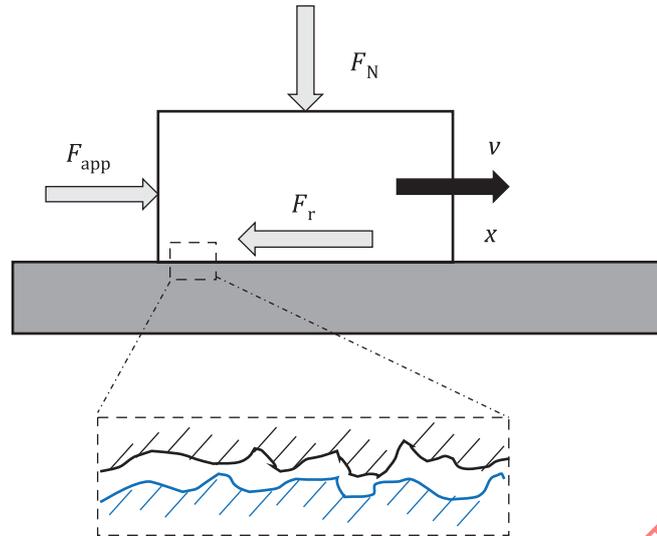
Key

F_N external force in the normal direction
F_{app} applied external force
F_r frictional force
v velocity
x displacement

Figure 3 — Friction emanating from the micro-geometry of the object surfaces.

It stems from the micro-geometry of the object which is usually not represented in 3D graphic representations. There are several types and models of friction, such as the coulomb (also known as dry, that opposes the relative lateral motion of two solid surfaces in contact), fluid (describes the friction between layers of a viscous fluid that are moving relative to each other), lubricated (a case of fluid friction where a lubricant fluid separates two solid surfaces), skin (a component of drag, the force resisting the motion of a fluid across the surface of a body) and Internal (the force resisting motion between the elements making up a solid material while it undergoes deformation).

In the simplest form, the resistive force from friction is computed simply by multiplying the friction coefficient and the force acting on the object in the normal direction of the object surface. Again, on the other hand, there exist more complex and dynamic models of frictional force, such as the Dahl, LuGre, Leuven and generalized Maxwell-slip models. Formula (3) shows the Dahl model equation for the frictional force as related to two object- or material-specific parameters, i.e. the stiffness and coulomb friction coefficients which "collectively" represent the detailed frictional property[5].

$$\frac{df_r^t}{dx} = \sigma \left(1 - \frac{f_r^t}{\mu_k f_r^n} sgn\left(v^t\right) \right) \tag{3}$$

where

$f_r^t(t)$ is frictional force (tangential);

f_r^n is frictional force (normal);

x is object displacement;

$v^t(t)$ is object velocity;

σ is stiffness coefficient;

μ_k is Coulomb friction coefficient.

4.4 Object texture

Object texture causes contact response in a similar way to friction, more due to the "micro" geometry and pressure distribution of the surface protrusion but resulting in the relatively "high" frequency elongated contact response (i.e. vibration). Figure 4 shows a close look at the surface protrusion of an object surface. The uneven fine structures of a surface could result in high-frequency vibrations in the "sliding" friction force. The frequency spectra for the object surfaces is obtained using the fast Fourier transform (FFT) from sliding trials on the surface. Such frequency components of the haptic vibration, which may change in time, can be captured as the impulse response behaviour using spectrogram-like representation or also using parametric models. Spectrogram refers to the plot of frequency response of a signal as they vary in time. Either way, each method again would require storage of several to many parameter values under different operating conditions to represent how the surface texture affects the haptic output in simulating object contacts or slidings. Culbertson et al. has suggested, using the linear predictive coding scheme (called the autoregressive model), storing and reconstructing vibrational haptic response at different normal forces and scanning (sliding) object velocities in a compact way[6].

Figure 4 — Example of object surface and one of its textures, seen in detail with magnification

5 Material property representation 1: extended material node

As an alternative to the current ad hoc practice, new attributes to the standard object material construct (such as the material or appearance node in X3D) for the haptic parameters are introduced as shown in the following code. The three most basic parameters, namely the stiffness (both static and dynamic), friction and texture, are all included as they are minimally necessary for mostly any haptic rendering algorithm. Note that the data formats for stiffness and friction are singular numeric values (constants) and for texture, a list of amplitude values corresponding to a fixed set of frequency components.

Material: X3DMaterialNode {

SFFloat	[in, out]	ambientIntensity	0,2 [0, 1]
SFColor	[in, out]	diffuseColor	0,8 0,8 0,8 [0, 1]
SFColor	[in, out]	emissiveColor	0 0 0 [0, 1]
SFFloat	[in, out]	shininess	0,3 [0, 1]
SFColor	[in, out]	specularColor	0 0 0 [0, 1]
SFFloat	[in, out]	transparency	0,8 [0, 1]

```
}
HapticMaterial:        X3DMaterialNode {
    SFFloat    [in, out]        stiffness        0,2 [0, 1]
    SFFloat    [in, out]        dynamicFriction 0,4 [0, 1]
    SFFloat    [in, out]        staticFriction   0,6 [0, 1]
    SFFloat    [in, out]        texture0,1 0,2 0,4 … [0, 1]
}
<Appearance>
    <Material
ambientIntensity="0,2"
diffuseColor="0,8 0,8 0,8"
emissiveColor="0 0 0"
specularColor="0 0 0"
shininess="0,2"
transparency-="0,8"
    />
    <Haptic_Material>
stiffness="0,4"
dynamicFriction="0,6"
staticFriction="0,8"
texture="0,1 0,2 0,4 …"
    />
</Appearance>
```

6   Haptic rendering node

The inclusion of just the three material properties (as suggested in Clause 5) is still limited; while it might be sufficient for use for a number of simple, popular and commonly used haptic rendering models, it is insufficient for more sophisticated, detailed and special-purpose rendering methods. For example, there exist many haptic rendering models as tailored for different:

— contact situations, such as slip, sliding and rolling;

— devices, such as those that can support areal, multi-contacts and compliant forces;

— object types, such as fluid and deformable objects.

Haptic rendering and force computation models for such situations require more detailed parameters in addition to these three. The detailed parameters collectively can form a group to represent a particular material "feature," such as stiffness and friction.

Thus, this document defines a construct that represents a particular haptic rendering method and required set of parameters which can be linked to a particular geometry or object whose haptic behaviour is to be simulated that way. For now, it has three different subclasses, namely rendering methods with regards to (but not limited to) the object or geometry's stiffness, friction and texture:

Haptic_rendering::SceneGraphNode

   String [in, out] type

   MFFloat [in, out] parameter_set [0 0 0 ...] [0, 1]

   Geometry [in, out] applie_to nil

Stiffness_rendering : Haptic_Rendering

Friction_rendering : Haptic_Rendering

Texture_rendering : Haptic_Rendering

Figure 5 illustrates how these new constructs apply in practice in the instantiated form. In the figure, three rendering methods are defined, each identifying the specific rendering methods, the required associated parameter set values and link to the associated object or geometry. This way, simply by extending the subclasses according to the different rendering methods, flexibility is easily achieved. Note that these different methods can be selectively applied to different parts of the geometry or objects to manage the level of detail and simulation performance.
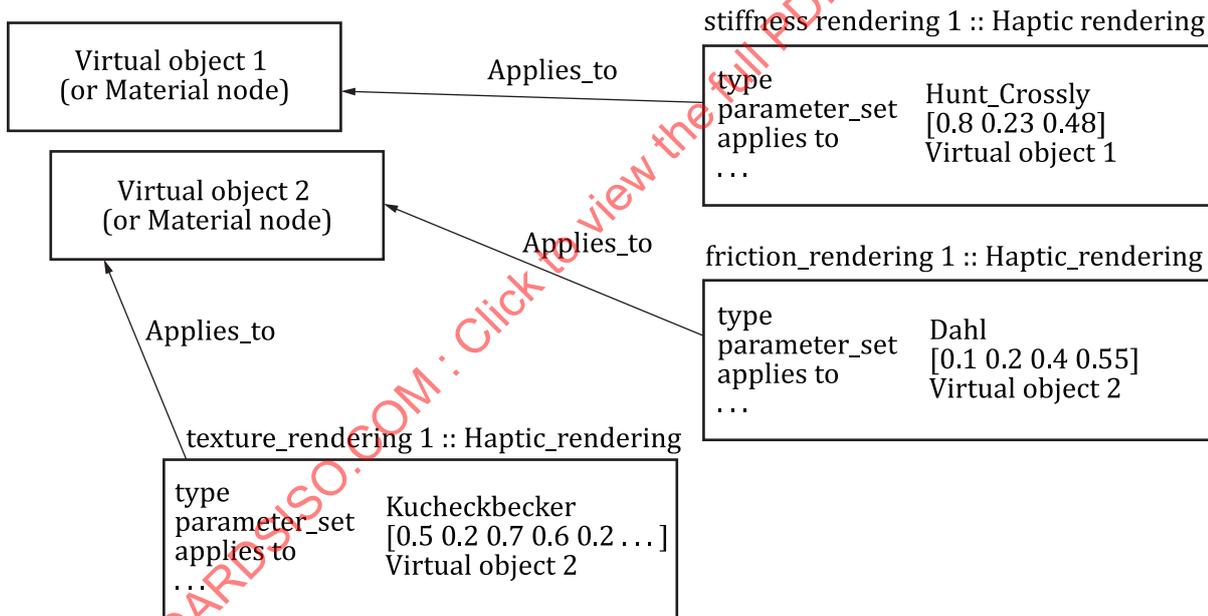
Two virtual objects (that have certain 3D geometry) are lined to three different "haptic" rendering nodes (or subclasses). Virtual object 1 is specified with a stiffness rendering by the Hunt-Crossley method[4], with the predefined parameter value set of [0.8, 0.23, 0.48], and virtual object 2 with the Kuchenbecker texture rendering[6] and Dahl friction rendering methods[7].

Figure 5 — Application of the new Haptic rendering construct

7   Conformity

A specific implementation of the object model for the material property representation and the indexing scheme for the associated haptic rendering algorithm specification may be tested for conformity in the following way. For a given implementation, check and verify if there exist the corresponding object