TOWARDS REAL-TIME MODELING AND HAPTIC RENDERING OF DEFORMABLE OBJECTS FOR POINT CLOUD-BASED MODEL-MEDIATED TELEOPERATION

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ABSTRACT
We propose a novel radial function-based deformation (RFBD) approach to enable real-time modeling and haptic rendering of deformable objects for point cloud-based Model-Mediated Teleoperation (pcbMMT). In the pcbMMT system, a time-of-flight camera is employed on the slave side to capture a 3D point cloud model of the remote environment. This environment model is transmitted to the master along with the estimated model parameters, including the dynamics of the object’s surface deformation and the physical properties such as the stiffness, friction coefficient, etc. Due to the simplicity of the RFBD approach, the model parameters of the remote environment can be obtained in real time. On the master side, a local copy of the environment model is maintained according to the received parameters. Both the haptic rendering and deformation simulation are based on this local model, running at 1kHz. Thus, a good compromise is achieved between the model accuracy and the computational time for online parameter identification. Experiments verify the feasibility of the proposed approach, and show the results of the object deformation for different model parameters.

Index Terms— point cloud model, radial function-based deformation, model-mediated teleoperation

1. INTRODUCTION
In the last few decades, the growth and progress of audiovisual communications has led to improved productivity and quality of experience in remote interaction scenarios like video conferencing, remote teaching, etc. With the benefits of this technology, users feel more present and experience an improved immersion in the remote environment. However, a complete immersive communication cannot be realized without the possibility to physically interact with remote objects [1]. To achieve such remote interaction, teleoperation systems have been developed to supply the user with haptic feedback in addition to the audio and video information.

Fig. 1. Overview of a typical teleoperation system (adopted from [1]). \( T_f \) and \( T_b \) are the forward and backward communication delays.

A teleoperation system, also referred to as a bilateral teleoperation system with haptic feedback, allows human users to interact with and to immerse themselves into a remote environment by means of slave and master devices which exchange force and position/velocity information over a communication link. As illustrated in Fig. 1, the slave robot follows the received position or velocity commands sent by the master. During the slave’s interaction with the remote environment, the haptic, visual, and audio signals captured by the sensors on the slave side are transmitted back to the master, and displayed to the user. Applications such as telepresence, telesurgery, teaching/training, entertainment, etc., can benefit from such a multimodal teleoperation system [2].

The presence of communication delays in the haptic channel introduced by the network, however, degrades both the system stability and transparency [3]. Ideal transparency means that the impedance perceived by the user is identical to the impedance of the remote environment. To address this issue, passivity-based control schemes, such as wave-variable transformation [4], have been developed. System stability (passivity) and transparency are, however, conflicting objectives in passivity-based teleoperation system design [3, 4]. This means that the classical passivity-based control approaches guarantee the system stability at the cost of degraded transparency.

To address both the stability and transparency issues in the presence of arbitrary communication delays, the concept of Model-Mediated Teleoperation (MMT) is proposed [5, 6, 7].

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The aforementioned MMT approaches use a simple surface geometry (e.g. a plane) to approximate the remote environment. However, in most cases the environment is quite complex. Xu et al. present a point cloud-based Model-Mediated Teleoperation (pcbMMT) approach to deal with complex object geometry for static and rigid objects in [11]. As illustrated in Fig. 3, a point cloud of the object surface is captured by a 3D sensor on the slave side and transmitted to the master. Lossless H.264/AVC compression is employed to compress the point cloud data before it is transmitted to the master. On the master side, a point cloud-based haptic rendering method is employed to locally generate the force feedback signals based on the received object surface model.

In this paper, we propose a novel radial function-based deformation (RFBD) approach which allows us to use the pcbMMT concept for deformable objects as well. Due to the simplicity of the RFBD model, a good compromise is achieved between the model accuracy and the computational time for online parameter identification. On the master side, both the haptic rendering and surface deformation can be simulated at 1kHz using the estimated physical properties of the object.

2. RELATED WORK

In the MMT approach, an object model with unknown parameters is first selected to approximate the remote environment. Then, these unknown parameters are estimated on the slave side and transmitted to the master in real time during the slave’s interaction with the remote environment. On the master side, a local object model can be built according to the received model parameters, and the force feedback signals are generated based on this local model without delay.

Online parameter identification for MMT systems is studied in [8, 12, 10], where a single degree of freedom mass-spring-damper model [8], a linear Kelvin-Voigt model [12, 10], and a non-linear Hunt-Crossley model [10] have been employed to approximate the remote environment. The model used to describe the object’s surface deformation in these works are, however, either too simple or object deformation is not taken into account. For the modeling of complex deformable objects, the multi-degrees of freedom Mass-Spring Models (MSM) or the Finite Element Models (FEM) are considered as the most popular methods, which are widely investigated in soft tissue simulations [13, 14]. However, an online parameter identification for MSM and FEM methods is impossible due to the huge computational complexity [14, 15].

Thus, the challenge of real-time modeling for deformable objects is to balance the model accuracy with the computational time for the parameter identification. In this paper, we propose a radial function-based deformation model for the pcbMMT system that achieves this aim.

3. RADIAL FUNCTION-BASED MODELING AND HAPTIC RENDERING

The parameters of the object model can be categorized into three parts: the surface geometry, the physical properties and the dynamics of the surface deformation. The choice of the object model is based on the following assumptions about the environment and the pcbMMT system:

- The surface geometry is described by a 3D point cloud which is captured by a 3D sensor. The point cloud contains no other information except its spatial position. All the points are massless, rigid, and independent units without any spring connection (see Fig. 4).
3.1. Environment modeling

In the theory of elasticity, the surface deformation of soft objects under external pressure is simply modelled as a contact problem between a rigid end-effector and an elastic half-space [16]. According to the geometry of the contact area, the surface deformation can be described by different radial functions with an infinite deformation area. Fig. 5(a) shows the deformation of an infinite elastic half-space with a force applied to it at a single point. The precise analytical solution of this problem given in [16] shows that the longitudinal displacement $z$ is proportional to the inverse of the radial distance $r$. According to this solution, the deformation at the contact position becomes infinite, which is impossible in our teleoperation system, since the contact area between the slave end-effector and the object surface is more than a single point. In addition, the deformation area on the object surface is infinite, which is too complicated for the object modeling. Thus, we use a sixth-order polynomial radial function with a finite deformation area to approximate the surface deformation of the object model. As illustrated in Fig. 5(b), the longitudinal displacement of the object surface $z$ as a function of the radial distance $r$ can be described as:

$$z(r) = \begin{cases} 
  c \cdot (R^2 - r^2)^3, & r \leq R \\
  0, & r > R 
\end{cases}$$

where $R$ is the radius of the deformation area depending on the material of the object. To reduce the number of unknown parameters, we define that $R$ is proportional to the maximal longitudinal displacement $z_{\text{max}}$, described as $R = n \cdot z_{\text{max}}$ ($n \in \mathbb{R}^+$). $c$ represents the parameter of the model dynamics depending on the object materials, the force inputs and the value of $R$. Although there is a visible difference in the surface deformation between the real and approximated models (Fig. 5), it is acceptable if the haptic rendering is accurate, since the visual information displayed to the user comes from the live video, and not from the virtual object model.

3.1.1. Longitudinal deformation

The object stiffness, damping factor and dynamics parameter $c$ can be estimated according to the longitudinal deformation of the object surface. Normally, when a force is applied to
the surface of a deformable object, the relationship between the normal force $f^n$ and the maximal displacement $z_{\text{max}}$ at the contact point can be described as $f^n \sim z_{\text{max}}^p$, where $p$ is a factor with a value between 1 and 2 in most cases [16, 17]. Thus, we use a second-order spring-damper model to approximate the force-displacement relationship on the slave side:

$$\hat{f}_n^s = k_1 \cdot z_{\text{max}} + k_2 \cdot z_{\text{max}}^2 + b \cdot v^n_s$$  \hspace{1cm} (2)

where $\hat{f}_n^s$ is the computed slave normal force based on this spring-damper model. $v^n_s$ are the measured slave velocity in the normal direction. $b$ denotes the damping factor. $k_1$ and $k_2$ are the stiffnesses for the first and second order.

A least-squares approach is employed to estimate the model parameters $(k_1,k_2,b)^T$ based on the known samples $(z_{\text{max}}, v^n_s, f^n_s)^T$,

$$(k_1,k_2,b) = \arg \min_{(k_1,k_2,b)} \| f^n_s - (k_1 \cdot z_{\text{max}} + k_2 \cdot z_{\text{max}}^2 + b \cdot v^n_s) \|_2^2$$  \hspace{1cm} (3)

where $f^n_s$ is the real slave normal force measured by the slave robot. The velocity $v^n_s$ can also be obtained by the slave robot. Meanwhile, we define a collision position $O$ as the point where a collision is detected on the object surface before deformation. Then, the displacement $z_{\text{max}}$ can be computed as the distance between the current slave position $x_s$ and the collision position $O$: $z_{\text{max}} = x_s - O$ as illustrated in Fig. 5(b).

In addition, according to Eq. (1), the displacement at the contact position can also be expressed as $z_{\text{max}} = z(0) = c \cdot R^6$. Suppose a perfect model match as $\hat{f}_s^m = f^n_s$, and combined with Eq. (2) we have

$$c = -k_1 + \sqrt{k_1^2 + 4k_2(f^n_s - bv^n_s)}/2k_2R^6$$  \hspace{1cm} (4)

Thus, the surface deformation of the object model can be uniquely determined using the estimated physical properties and the applied contact force. On the master side, the deformation of the object surface can be simulated by using the master normal force $f^n_m$ and velocity $v^n_m$ instead of $f^n_s$ and $v^n_s$.

#### 3.1.2. Tangential deformation

Due to the surface friction, lateral motions of the slave end-effector on the object surface cause tangential deformations [17]. Applying a lateral force which is smaller than the maximal static friction results in local dragging. This means that the tangential deformation of the object surface is limited to a local area, while the contact point is stretched tangentially without sliding relative to the slave end-effector (Fig. 6(b,c)). If the lateral force is larger than the maximal static friction, the contact point between the end-effector and the object surface is released, and a relative sliding occurs [17]. As illustrated in Fig. 6(d), we use a global sliding of the deformation area to approximate this effect. This means that the deformation area as a whole follows the end-effector’s motion on the object surface without further local dragging. For the local dragging, we use a shearing algorithm to approximate it, which is described as follows:

$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} 1 & 0 & s \\ 0 & 1 & s \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$  \hspace{1cm} (5)

where $(x',y',z')$ and $(x',y',z')^T$ are the same point in the deformation area on the object surface before and after the local dragging. $s$ is the shearing factor, which depends on the applied tangential force and the physical properties of the object. Given the aforementioned assumption of isotropic physical properties, the slave lateral force can be expressed as:

$$f^l_s = k_1 \cdot \Delta r + k_2 \cdot (\Delta r)^2 + b \cdot v^n_s$$  \hspace{1cm} (6)

where $f^l_s$ is the measured slave lateral force. $\Delta r$ is the
dragging distance of the contact point. According to Eq. (5), \( \Delta r \) can be expressed as:

\[
\Delta r |_{z=z_{\text{max}}} = \sqrt{(\Delta x)^2 + (\Delta y)^2} |_{z=z_{\text{max}}}
= \sqrt{(x' - x)^2 + (y' - y)^2} |_{z=z_{\text{max}}}
= \sqrt{2x_{z_{\text{max}}}}
\]

(7)

Combined with Eq. (6) we have:

\[
s = -\sqrt{2k_1z_{\text{max}}} + \sqrt{2k_1^2z_{\text{max}}^2 + 8k_2z_{\text{max}}(f_s + bv_s)}
\]

(8)

Thus, using the estimated physical properties and the applied lateral forces, the tangential deformation can be determined. On the master side, instead of \( f_s' \) and \( v_s' \), we use the master lateral force \( f_m' \) and velocity \( v_m' \) to simulate the surface deformation of the object model.

Note that the surface friction coefficient \( \mu = \frac{f_s'}{f_m'} \) can only be estimated when there is a relative sliding between the slave end-effector and the object surface.

3.2. Haptic rendering

A combination of a point cloud-based haptic rendering approach [18] and a friction cone method [19] is employed to render the force feedback signals on the master side. Due to the simplicity of the object dynamics model, both the haptic rendering and the deformation simulation can run at 1kHz. As illustrated in Fig. 7, the force generated on the master side can be expressed as:

\[
f_m' = k_p(x_m - x_p) \cdot \hat{e}_i \quad \text{and} \quad f_s' = k_p(x_m - x_p) \cdot \hat{e}_n
\]

(9)

where \( k_p \) is the virtual stiffness between the master proxy and Haptic Interaction Point (HIP). \( x_p \) and \( x_m \) are the positions of the master proxy and HIP. \( \hat{e}_i \) and \( \hat{e}_n \) denote the tangential and normal vectors of the contact surface computed by the point cloud. If the master HIP is in the friction cone determined by the position of the master proxy and the surface normal, the tangential deformation of the object surface is limited to a local dragging. Otherwise, it becomes a global sliding.

4. EXPERIMENTAL EVALUATION

Setup The SensAble PHANTOM Omni® haptic device is used for the evaluation. The simulated environment contains a simple 3D membrane composed of 150 by 150 points placed in the \( z = -0.1 \) plane with a surface normal of \((0, 0, 1)^T\). All the programs run on a 3.33GHz Intel® Core(TM) i5 desktop PC with 4GB RAM.

Results The simulation results of the longitudinal and tangential deformations are shown in Fig. 8. The physical properties are set as fixed values. Changing the ratio between the deformation radius \( R \) and the maximal longitudinal displacement \( z_{\text{max}} \) leads to different visual deformations of the object surface. Fig. 8 shows the surface deformation in side and top views for the values of \( R : z_{\text{max}} = 3 : 1 \) and \( R : z_{\text{max}} = 6 : 1 \).

During the interaction, the master position and force signals are recorded. As illustrated in Fig. 9, at time \( t_1 \) the master HIP makes contact with the membrane, leading to an increasing \( z \)-directional force. At \( t_2 \), a lateral motion starts, resulting in a tangential deformation and an increasing \( x/y \)-directional force in amplitude. At \( t_3 \), the lateral force reaches the maximal static friction of the object surface. Thus, a global sliding occurs, and the lateral force stays equal to the surface dynamic friction. After \( t_4 \), the contact is released.

In addition, the online parameter identification described by Eq. (3) is tested with the help of the GSL linear algebra library (http://www.gnu.org/software/gsl/). The computational time for estimating the physical properties \((k_1, k_2, b)^T\) with 100 samples \((z_{\text{max}}, v_s', f_s')^T\) is less than 1ms, which achieves the requirement of real-time estimation.
Fig. 9. Position and locally rendered force signals of the master HIP during its interaction with the membrane.

Note that the ratio value \( R : z_{\text{max}} \) is manually chosen in our experiment. However, this value represents a certain physical property of the object material, which could couple with other physical properties such as stiffness, tensor applied to the surface, etc. A theoretical analysis for this issue is necessary to model a more accurate surface deformation. This will be addressed in our future work.

5. CONCLUSION

In this paper, we propose a novel radial function-based deformation (RFBD) approach to extend the point cloud-based Model-Mediated Teleoperation (pbcMMT) system to work for deformable objects. The geometry of the object surface is described by a point cloud captured by a 3D sensor. The longitudinal and tangential deformation of the object surface is approximated by the RFBD model and a shearing algorithm. Due to the simplicity of the RFBD model, the estimation of the model parameters can be performed in real time. In addition, both the deformation simulation and haptic rendering on the master side can run at the desired rate of 1kHz. Experimental evaluation verifies the usability of the proposed approach.

In future work, more theoretical analysis for complex object geometry will be made to improve the accuracy of the deformation model. In addition, subjective tests will be conducted in a real teleoperation system to evaluate both the subjective experience and the objective task performance.

6. REFERENCES


