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Thermal modeling for material identification

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When the hand touches an object, the changes in skin temperature provide information about the object's thermal properties that assist in material identification. This paper introduces thermal models that have been developed to characterize the skin temperature responses during hand-object interactions. These models are able to incorporate various material properties and contact conditions for different hand-object interaction scenarios and can predict the thermal responses of the skin and object during contact. Based on the modeling work, realistic thermal feedback associated with contact can be created with a thermal display to facilitate object identification in virtual environments or teleoperated robotic systems.

1. Introduction

When the hand is brought into contact with an object, the changes in skin temperature and the corresponding perceived coldness are a function of the thermal properties of the object. Materials with high thermal conductivity in general feel colder to touch because they extract a large amount of heat from the hand during contact. For example, we often find that a metal object feels colder than a wooden object of the same temperature due to the higher thermal conductivity that metal possesses. It has been shown that people can distinguish between materials on the basis of thermal cues when the difference in their thermal properties is relatively large, that is, when their thermal conductivity is differed in of the order of 70% (Jones and Berris, 2002), their thermal diffusivity is at least 43% apart (Bergmann Tiest and Kappers, 2009), or their contact coefficient is differed by a factor of three or more (Ho and Jones, 2006). These results indicate that thermal cues can be useful for material identification and discrimination, especially under the situations that an object must be identified with ambiguous or absent visual information.

Modeling the heat transfer process during hand-object interactions is useful for object simulation in virtual environments (Jones and Ho, 2008) and automatic material identification in robotic applications (Bhattacharjee et al., 2015). In the former applications, a thermal model can be used to predict the thermal responses of the skin during contact and the derived control algorithms for the thermal display should provide realistic thermal feedback associated with contact. In the latter applications, a thermal model can be applied to situations in which a tactile sensor, instead of a human finger, is making contact with an object and automatic recognition of the object's material can be achieved by comparing the predicted and measured data of the temperature responses during contact.

2. Thermal modeling

The thermal interaction between the skin and an object in contact with the skin is dominated by transient heat conduction. When the hand touches an object whose temperature is lower than the skin temperature, which is a common case in daily experience, heat flows out of the skin during contact and coldness is perceived. The heat transfer process between the skin and the object is complicated, involving factors from the human side (e.g. skin temperature, skin material properties, blood perfusion etc), the object side (e.g. object temperature, object material properties, object geometry, surface texture etc) and contact conditions (e.g. contact force etc).

When modeling the thermal interaction during hand-object interactions, it is commonly assumed that the temperature variation is only significant in the direction perpendicular to the contact surface for both the skin and object (1-D assumption) and that the skin and object are inanimate materials with semi-infinite dimensions (semi-infinite body assumption). With these assumptions, the thermal interaction can be simplified to a "two semi-infinite bodies in contact" problem. This model predicts that the surface temperatures of the skin and object would change instantaneously to an interface temperature at the moment of contact and would maintain constant throughout the contact period. The interface temperature only depends on the thermal properties and initial temperatures of the skin and object. The thermal property that governs this process is the contact coefficient, which is the square root of the thermal conductivity and heat capacity, and it acts as a weighting factor that determines whether the interface temperature will more closely approach the initial temperature of the skin or the object (Incropera and DeWitt, 1996). This model provides a basic description of the thermal process during contact and has been applied for object simulation in virtual environments (Yamamoto et al., 2004; Ho and Jones, 2007) and model-based material recognition in robotics (Bhattacharjee et al., 2015).

One major drawback of the "two semi-infinite bodies in contact" model is that it assumes that the contact is ideal and neglects the thermal contact resistance at the skin-object interface. This assumption results in a discrepancy between the predicted skin temperature responses and the measured temperature data, which show that the surface temperature of the skin change with time during the contact period. Analyses of the skin temperature responses during contact have indicated that thermal contact resistance has a significant effect on the thermal responses of the skin over the typical contact force range of 1 to 2 N (Yamamoto et al., 2004; Jones and Ho, 2008). Ho and Jones (Ho and Jones, 2008) thus improved the "two semi-infinite bodies in contact" model by taking into consideration thermal contact

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resistance, which has been shown to relate to the contact force and the surface textures of the skin and object (Yovanovich, 1981). This model was able to provide precise prediction on the time course and amplitude of the skin temperature change over 20s of contact, with a prediction error of less than 1°C over the range of contact forces typically used in manual exploration. The good performance of this model indicates that the 1-D assumption, the semi-infinite body assumption and the neglect of the effects of blood perfusion and metabolic heat generation do not appear to have a significant effect on the skin's thermal responses during contact, at least in the range of the contact force and the time duration investigated by Ho and Jones (2008).

One limitation of the model proposed by Ho and Jones (2008) is that it does not account for the geometry of the object in contact. Object geometry in fact has a significant influence on the skin temperature response during contact. Consider, for example, the difference in perceived coldness when making contact with an aluminum block and a piece of aluminum foil. A recent study measured the changes in skin temperature when touching various materials with varying geometry and it showed that skin temperature responses depended on both the material and geometry of the object in contact and that the influence from the object geometry primarily appeared at a later phase of contact (> 5s) (Ho, submitted).

The thermal model proposed by Bergmann Tiest (2007) takes into consideration the influence from the object geometry on the heat transfer process during hand-object interactions. This 1-dimensional finite element model assumes a constant finger temperature to account for the effect of blood perfusion and considers the thermal contact resistance at the skin-object interface. The model predicts that thick objects would extract more heat from the finger during contact and therefore feel colder to touch than thin objects, which is consistent with the daily experience during object manipulation. However, the predictions were not directly compared with empirical measurements, so it is unclear to what extent this model captures the actual heat transfer process during contact. Moreover, the constant finger temperature assumption makes it difficult to implement to thermal displays for object simulation and automatic material recognition system.

To model the influence from the object geometry on the temperature responses at the skin surface, Ho (submitted) proposed a lumped-capacitance model, in which the skin is modeled as a semi-infinite body and the object is modeled as a lumped system (Incropera and DeWitt, 1996). The model predictions and the measured data were consistent in characterizing the time course and amplitude of the skin temperature change during 20s of contact with differences typically being less than 1°C for metal samples that spanned a range of thickness (3 - 30 mm). For materials with low thermal conductivity (e.g. plastic and foam), the model couldn't capture the rapid temperature change at the moment of contact and tended to predict a gradual decrease in the skin temperature throughout the contact period. Nevertheless, as the influence from the object geometry is most obvious for materials with high conductivity (e.g. metal), this analytical model could be useful for analyzing the thermal cues used for thickness identification.

3. Conclusion

Various thermal models have been proposed for modeling the skin temperature responses during hand-object interactions (for full review, see Jones and Ho 2008). The choice among the various models depends on the particular application domain for the model, its validation in empirical studies, and how readily the model can be implemented in a thermal display or a robotic system.

In short, thermal modeling for hand-object interactions should serve as a knowledge base to understand the physical process underlying material identification based on thermal cues and contribute to the development of thermal displays for material simulation and automatic material identification system based on thermal feedback.

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