Multi-dimensional force sensor for haptic interaction: a review

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Abstract Haptic interaction plays an important role in the virtual reality technology, which let a person not only view the 3D virtual environment but also realistically touch the virtual environment. As a key part of haptic interaction, force feedback has become an essential function for the haptic interaction. Therefore, multi-dimensional force sensors are widely used in the fields of virtual reality and augmented reality. In this paper, some conventional multi-dimensional force sensors based on different measurement principles, such as resistive, capacitive, piezoelectric, are briefly introduced. Then the mechanical structures of the elastic body of multi-dimensional force sensors are reviewed. It is obvious that the performance of the multi-dimensional force sensor is mainly dependent upon the mechanical structure of elastic body. Furthermore, the calibration process of the force sensor is analyzed, and problems in calibration are discussed. Interdimensional coupling error is one of the main factors affecting the measurement precision of the multi-dimensional force sensors. Therefore, reducing or even eliminating dimensional coupling error becomes a fundamental requirement in the design of multi-dimensional force sensors, and the decoupling state-of-art of the multi-dimensional force sensors are introduced in this paper. At last, the trends and current challenges of multi-dimensional force sensing technology are proposed.

Keywords Haptic interaction; Virtual reality; Multi-dimensional force sensor; Elastic body; Decoupling; Force sensor calibration

1 Introduction

At present, virtual reality technology has been widely used in various fields, such as industrial assembly, telerobot, service, medical training, rehabilitation, education, entertainment, and so on. As one of the key techniques, haptic interaction has been paid increasingly attentions by researchers[1-3]. Multi-dimensional force sensor is a foundational element for haptic interaction systems[4-5]. For a typical haptic interaction system, it consists of haptic display device, audio-video devices, three-dimensional geometric model, physical-based haptic rendering, and force sensor, as shown in Figure 1.

According to the measurement principle, the multi-dimensional force sensors can be classified

Figure 1 A typical haptic interaction system.
into the following types: resistance strain type, piezoelectric type, capacitive type, optical fiber type, etc. Most of the multi-dimensional force sensors are based on strain gauges.

Metal-foil strain gauge is the sensing element of resistance strain type multi-dimensional force sensor that detects the force signal based on strain-resistance effect. Shape change of wire gauze subjected to forces or stresses results in its resistance variation, and accordingly transformation to electric signal output. Among the multi-dimensional force sensors based on many measured principles, resistance strain type force sensor is the most widely used one at present. It has many advantages, such as high sensitivity, wide measurement range, high reliability, proven technique, etc. However, it has some disadvantages including poor dynamic response, great influence of external factors on Wheatstone bridge. The key issue of the design of this kind of sensor is how to design a reasonable and optimum mechanical structure of the elastomer.

Piezoelectric multi-dimensional force sensor is a kind of potentiometric sensor which realizes the measurement of force/torque (F/T) based on piezoelectric effect. The piezoelectric effect is usually also used for tactile sensor fabrication. At present many researchers have studied on the piezoelectric component as a sensing element to directly measure the multidimensional forces/torques. Liu et al. proposed a piezoelectric six-dimensional heavy F/T sensor based on Stewart structure. The sensor achieves the effect of enhancing the heavy load sharing ability of piezoelectric wafer while the radius of the manipulator is increasing. Li et al. studied large-range six-dimensional F/T sensor, but no universal analytical mathematical model was obtained, and it is difficult to realize the miniaturization of the force sensor. The main characteristic of piezoelectric material is that it has high inherent frequency, which is especially suitable for dynamic measurement. However the main disadvantages of piezoelectric material are that it is insensitive to the static force and it is easy subjected to the external electromagnetic noise.

Capacitive multi-dimensional force sensors can measure the multi-dimensional F/T by setting a couple of capacitors and changing the relative gap between electrodes. Because of high sensitivity and flexibility, many researchers have conducted research on the capacitive force sensor. Kim et al. presented a capacitive type six-axis F/T sensor with parallel plate capacitors embedded in a flexure structure. Lee et al. developed a capacitive type six-axis F/T sensor in which the sensing elements are aligned in plane, and can be fabricated on a single printed circuit board. Accordingly, the sensor's structure is simple and processing is easy. Kim et al. presented a novel capacitive six-axis F/T sensor with six capacitive sensor cells for robot applications, and proposed a sensor design with parallel and orthogonal arrangements of sensing. Over the past decade, micro-electromechanical systems (MEMS) capacitive F/T sensors have been used in specific domains, such as high temperature and magnetic fields. This is attributed to the attractive features of MEMS capacitive sensors, such as high sensitivity, low noise, low power consumption, and insensitivity to temperature, and so on. In order to resolve the problem of high cost of current commercial F/T sensors, Jacob et al. presented a new design for an inexpensive and robust F/T sensor using MEMS barometers. This sensor can be assembled in two days for less than 20 USD, but its accuracy is much lower than that of commercial sensors. Brookhuis et al. designed a silicon capacitive three-axis F/T sensor that can be used to measure the interaction forces between a human finger and the environment, but the resolution of the sensor need to be improved. In spite of their advantages, the application of the capacitive multi-dimensional F/T sensors is restrained because of their large parasitic capacitance interference.

The objective of this review paper is to give an overview about the resistance strain type multi-dimensional force sensor which is the most widely used for haptic interaction at present. In section 2, the development of mechanical structures of the multi-dimensional force sensors are introduced. Then calibration method and problems in calibration are described in section 3. This is followed by presentations
of coupling error and static decoupling methods in section 4. At last, we indicate the trends and challenges of the multi-dimensional force sensors.

2 Mechanical structures of multi-dimensional force sensor

The key mechanical component of all kinds of multi-dimensional force sensors is the elastic body usually called elastic beam, which responds to the external acting F/T by deformation. Depending on the mechanical structure of the elastic beam, the mechanical structures of multi-dimensional force sensor are usually classified into two types: integrated structure and Stewart parallel structure. Multi-dimensional force sensor with integrated structure includes cylindrical elastic beam structure, cross elastic beam structure, asymmetric radial elastic beam structure, and composite elastic beam structure. The comparisons of main features of six-dimensional F/T sensors with various mechanical structures are given in Table 1. For six-dimensional F/T sensors, the main principle is to test three directional forces and three dimensional moments by measuring the related strains of the elastic beam by strain gauges.

<table>
<thead>
<tr>
<th>Mechanical structure</th>
<th>Pros</th>
<th>Cons</th>
<th>Typical design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylindrical beam</td>
<td>Large load capacity, good shock resistant ability</td>
<td>Low sensitivity in vertical direction, serious inter-dimensional coupling</td>
<td>[25,26]</td>
</tr>
<tr>
<td>Cross beam</td>
<td>High symmetry, compact structure, large rigidity, easy to machine, simplified mechanical model due to a flexible link</td>
<td>Existence of interdimensional coupling and radial effect</td>
<td>[27,28]</td>
</tr>
<tr>
<td>Asymmetric radial beam</td>
<td>Large rigidity, easy to set the coordinate system</td>
<td>Difficult to machine, and existence of nonlinear interdimensional coupling</td>
<td>[29]</td>
</tr>
<tr>
<td>Composite beam</td>
<td>No-coupling measurement can be realized.</td>
<td>Complicated structures with Combination of elements; Greatly affected by machining and assembly precision</td>
<td>[30]</td>
</tr>
<tr>
<td>Stewart platform</td>
<td>Large rigidity, super stability, large load capacity</td>
<td>It is difficult to achieve the forces and moments isotropy</td>
<td>[31]</td>
</tr>
</tbody>
</table>

A typical cylindrical elastic beam structure of 6 degree of freedom (DOF) F/T sensors are illustrated in Figure 2, which is called Watson force sensor developed by DRAPER Laboratory in the United States[24]. It consists of three vertical thin beams that are milled from a cylinder and distributed in the circumferential direction of 120°. The measuring circuit of the sensor is placed in the hollow cylinder. The F/T sensor has simple structure and high sensitivity but large interdimensional coupling errors, thus it needs decoupling calculation to obtain precise six-dimensional forces and torques. And the anti-overload ability of the sensor is very low, which means it is vulnerable to damage.

A six-dimensional F/T sensor early developed by Stanford Research Institute (SRI) is depicted in Figure 3, which is also a vertical elastic beam based cylinder structure[25]. It is made of an aluminum cylinder with 75mm diameter and has eight narrow and long elastic beams. Each beam has a small groove in the neck to make the neck only transmit forces, and make the torque effects be very small. Strain gauges are attached on both sides of the other end of each beam.

Figure 4 and 5 depicted typical crossbeam structure and non-radial three-beam structure of 6 DOF F/T sensors, respectively. The crossbeam structure shown in Figure 4 was brought forward by Japan Daiwa Balance Co., Ltd. based on the wrist force sensor developed in JPL Laboratory[26]. It is an integral spoke structure with a flexible link between the crossbeam and flange, thus simplified mechanical model of the elastomer as a cantilever beam. Strain gauges attached on the four main beams compose 6 Wheatstone bridges for six-dimensional force/torque measurement. The SAFMS 6 DOF F/T sensors, developed in 1987 by Hefei institute of intelligent machinery, in collaboration with Southeast University, adopted this
A sensor with a non-diametric three-beam centrosymmetric structure is shown in Figure 5. The inner edge and outer edge of the sensor are fixed on the arm and claw of a robot respectively, and the force exerted to the sensor is transmitted by three beams tangle to the inner edge. Two pair of strain gauges is attached to top, bottom, left, and right sides of each beam, so that six groups of half-bridges can be formed. Exact solution of the six-dimensional forces/torques can be obtained by decoupling the six groups of bridges. This kind of force sensor has high rigidity. It was first proposed by Carnegie Melon University, and also studied by Huazhong University of Science and Technology, that is HUST-FS6 6 DOF F/T sensor\textsuperscript{28}. The aforementioned structures are cross-beam or vertical-beam structures with simple monolithic elastic elements, whereas interdimensional coupling is serious. In 1982, Schott proposed a six-dimensional F/T sensor with double-ring composite elastic beam structure\textsuperscript{29}, as depicted in Figure 7. This structure with combination of elements can reduce or eliminate the interdimensional coupling.

Figure 2 Draper Watson’s 6 DOF F/T sensor\textsuperscript{25}.

Figure 3 SRI 6 DOF F/T sensor\textsuperscript{24}.

Figure 4 Crossbeam structure based 6 DOF F/T sensor\textsuperscript{27}.

Figure 5 Non-radial three-beam based 6 DOF F/T sensor\textsuperscript{29}.

Figure 6 Crossbeam structure based SAFMS 6 DOF F/T sensor.

Figure 7 Schematic view of a six-dimensional F/T sensor with composite elastic beam\textsuperscript{29}. 

mechanical structure\textsuperscript{27}, as seen in Figure 6.
Figure 8 shows a classic structure of another commonly used 6 DOF force sensor based on Stewart platform, a 6 DOF parallel mechanism proposed by Stewart in 1965. The six spherical hinges of the upper or lower platform are distributed around the same circle. They are semi-symmetric, i.e., spherical hinges 1, 3, 5 and 2, 4, 6 distributed at intervals of 120°, respectively. Six elastic beams between the upper and the lower platform produce strains when six components of force apply to the platform. Therefore the 6 DOF forces/torques can be obtained from the output of the Wheatstone bridge comprised of strain gauges attached to the ring of elastic beams. The difference from the aforesaid two kinds of vertical beam structure is non-integral structure that the upper and lower of the platform are connected with the six elastic beams by spherical hinges. The spherical linkage means the low inherent frequency, so that the Stewart parallel structure based multidimensional force sensor is only suitable for the static force/torque measurement.

The above mentioned mechanical structures are classical structures of elastic beams. In recent years, many researchers presented some novel mechanical structures of elastic beam on the basis of the classical structures to improve the performance of multi-dimensional force sensor. A large-range six-axis force sensor made by machining dumbbell grooves in cross beams is developed by Changchun Institute of Optics, which has high sensitivity while ensuring a large measurement range. Schematic diagram of the elastic beams of the sensor is depicted in Figure 9. Mastinu et al. designed a six-axis F/T sensor with a novel mechanical structure, seen in Figure 10a. The sensing element of this sensor is a quasi-statically determined three spoke structure constrained by virtue of elastic sliding spherical joints, seen in Figure 10b, which is designed to avoid friction. Experimental results demonstrated that the sensor have a good performance in linearity, crosstalk and dynamic behavior. Liang et al. developed a novel miniature four-dimensional force sensor with elastic elements consisted of circular diaphragm and cantilever beam, seen in Figure 11. The sensor comprises of a sensor tip, an upper cover, a base frame and elastic elements. Hu et al. presented a novel elastic element design method of a six-dimensional F/T sensor with a floating beam that changing the floating beam to H-beam to increase the stiffness of the sensor and improve the dynamic performance. Songet al. proposed an improved mechanical structure of elastomer design for three-dimensional force sensor miniaturization, which combines the cross beam and central straight beam to achieve the sensation of 3 dimensional forces, shown in Figure 12. It is suitable for haptic interaction owing to its small size with 28mm diameter.
3 Calibration of multi-dimensional force sensor

The static calibration of sensors plays an important role in testing, and it is a necessary step to ensure the high precision of sensors. For a multi-dimensional F/T sensor, static calibration is to exert standard forces of different magnitudes and directions on the sensor to obtain the corresponding output, and to evaluate and correct its performance by establishing the relationship between them based on curve fitting.

3.1 Calibration method

At present, the static calibration methods of multi-dimensional force sensors mainly include tension-compression dynamometer method, standard weight method and other standard force generator consisting of force generating equipment and high precision single-axis sensor. Due to the diversity of sensor structures, there is no universal calibration device. Standard weight method is mainly introduced in this section. The calibration test bench was developed by Robot Sensor and Control Lab of Southeast University. Figure 13 shows the force/torque loading test bench.

The six-dimensional F/T sensor to be calibrated is fixed on the scalable and rotatable indexing plate, which is fixed on the base of the test bench, and the calibration shaft passes through the central axis of the sensor. The sliding rods on both sides of the test bench can be adjusted and fixed to a certain height, so that the steel wire suspending the standard weights presents a horizontal straight line between the calibration shaft and the pulley, that is, it is parallel to the Y axis in Figure 13.

On the test bench, six linear independent standard force/torque components are applied to the six-
dimensional F/T sensor, respectively, and the output voltage values of the corresponding channels are recorded. Ideally, in the static calibration experiment, each force/torque component can be loaded only once under the condition that the applied standard force/torque is unbiased and the sensor is pure linear. However, due to the deviation of loading force/torque and the non-linearity of six-dimensional F/T sensor in the actual calibration process, the error of data obtained by loading only once is large. In practice, the method of average value obtained by loading many times is often adopted.

For micro F/T sensors, such as submillimeter multi-dimensional F/T sensor developed using silicon microfabrication technology, it is usually calibrated by applying gravitationally generated force onto its structure. This method, however, is difficult to implement. Electromagnetic force was used to calibrate the F/T sensor in reference. An aluminum cross-beam is suspended over, and placed at the center of the sensor. During calibration, the sensor is placed in a magnetic field and current is driven through the aluminum beams to produce force electromagnetically. Schematic view of the sensor design and calibration method is illustrated in Figure 14. Precise control of the magnitude of the electromagnetic force can be achieved owing to its relationship to current and magnetic field strength.

3.2 Problems in calibration

For a multidimensional F/T sensor, due to the resistant-strain effect based measurement principle and manufacturing errors, there is a mutual coupling among the output channels of the sensors. The inter-dimensional couplings are complex and difficult to describe accurately in theory. The experimental method is usually used to calibrate the relationship. However, due to the limitation of the experimental equipment and method, the force/torque cannot be directly applied to the center point of the force sensor, or the force direction is deviated a bit from the theoretical direction when the sensor is calibrated. This will result in interference among the six dimensional force components and limit the calibration precision of the sensor.

4 Coupling errors and decoupling methods

For an ideal six-axis F/T sensor, the voltage value of each output channel only depends on the applied force/torque on this channel, and is completely insensitive to the force/torques on the other five channels. However, due to the structural design of the sensor, the accuracy of mechanical processing, bonding technique of strain gauges, transverse effect of strain gauge and detection method, almost every component of force/moment acting on the sensor will affect all the output signals of the force sensor, which is called inter-dimensional coupling. The measurement error due to the coupling between dimensions is called inter-dimensional coupling error. The inter-dimensional coupling problem is main factor limiting measuring accuracy of multi-dimensional F/T sensors, so we must decouple the output signals to reduce or eliminate coupling errors.

Generally, there are two decoupling methods for multi-dimensional F/T sensors. One is hardware decoupling method, which starts with structural design and mechanical manufacturing process to eliminate the coupling errors. But this method is difficult to implement and greatly increases the cost of sensor manufacturing. Song et al. developed a novel four-dimensional F/T sensor with a novel self-decoupled mechanical structure for human-computer interaction, seen in Figure 15. The experimental results...
demonstrated that the four-axis F/T sensor with self-decoupled structure have the maximum measurement error of 1.5% Zhao et al. proposed a mechanical decoupling method for parallel three-dimensional force sensors, which uses rolling friction instead of sliding friction to reduce coupling\cite{40}. Wu et al. designed a six-dimensional force sensor with self-decoupling structure\cite{41}, but precise slip clearance and groove are needed, and the contact force between elastomer and groove side wall will produce additional coupling. The other method is software decoupling. The traditional static decoupling method, which is most widely used at present, is to solve decoupling matrix based on the least square method. This method is simple in principle and can realize online decoupling. Commercial sensors such as six-dimensional F/T sensors produced by ATI and AMTI Companies adopt this method to decouple. However, because of the matrix inversion in this method, it is easy to appear ill-conditioned matrix, so that a small perturbation of experimental data may make the decoupling accuracy change greatly. With the wide application of neural networks in many fields in recent years, various improved neural networks have been used in the static decoupling research of multi-dimensional force sensors\cite{42-44}. Song et al. proposed some static decoupling methods based on coupling error modeling\cite{45}, combination of SVM (Support Vector Machine) and coupling error modeling\cite{46}. The inter-dimensional coupling error can be reduced to less than 1.5% F.S.

5 Trends and challenges

Multi-dimensional F/T sensors technology has been studied for more than 40 years. With the rapid progress of the robot, haptics, human-computer interaction and virtual reality techniques, the force sensor as one of the important sources of the interactional information has been continuously improved. The development trends and challenges of the force sensor research are discussed as follows.

5.1 Trends

With the emergence of various new materials, as well as the development of mechanical manufacturing technology, MEMS and 3D printing technologies, the precision and reliability of multi-dimensional force sensor will be greatly improved.

Design of new mechanical structures of elastic beam for the purpose of higher sensitive and lower interdimensional coupling is always the direction of multi-dimensional force sensor research. However, as the progress of semiconductor technology and MEMS technology, multi-dimensional force sensors develop towards miniaturization\cite{47}, which leads to the force sensor will be more widely used in biomedicine and virtual reality fields such as minimally invasive surgery, diagnostics tools, remote surgery, rehabilitation, virtual training, haptic system, and so on\cite{48}.

On the one hand, many tasks like the force feedback of the maglev control system\cite{49} and the haptic interaction of the minimally invasive robotic surgery\cite{50}, require the real-time measurement of multi-dimension force signal, which makes the dynamic performance of multi-dimensional force sensor be paid more attentions than before. On the other hand, as the wearable haptic devices become the pursued objective of haptic interaction design, the multi-dimensional F/T sensor has been called for miniaturization, softness and wearability. Furthermore, the 3D printing technology starts applying to fabrication of multi-dimensional force sensors. Figure 16 shows a 3D-printed cross elastic beam of 6 DOF F/T sensors by using PEEK material manufactured by Robot Sensor and Control Laboratory at Southeast University,
which demonstrated to be more sensitive to the acting force/torque.

5.2 Challenges

As the development of virtual reality and augment reality, the devices supporting the multi-perception and interaction become more and more important, which requires the force sensors have higher precision, better dynamic performance and lower cost. Therefore, the multi-dimensional force sensor for haptic interaction faces some challenges.

5.2.1 Dynamic calibration and compensation

For haptic interaction or robot grasp task, the efficiency of online force sensing and feedback is highly dependent on the performance of multi-dimensional force sensor. The real-time haptic interaction or robot grasp task requires good dynamic performance of the force sensor. However, due to the low stiffness of elastic element and the adhesive strain gauges, the inherent frequency of resistive strain gauge based multi-dimensional force sensor is usually no more than 20KHz. Although it completely meet the dynamic requirement of haptic interaction or robot grasp tasks, but the inherent frequency will be descended as the load increases owing to the equivalent mass increasing. That means once the force sensor is installed on force feedback device or manipulator, its working bandwidth will be reduced a lot. Therefore, the dynamic performance of multi-dimensional force sensor needs to be compensated to improve its dynamic performance.

Currently, the research on multi-dimensional force sensor mainly concentrates on the improvement of mechanical structures of elastic element, static calibration, and decoupling methods, whereas dynamic calibration and performance analysis are little. And there is no dynamic calibration guideline for multi-dimensional force sensors. PTB in Germany has done a lot of research on dynamic calibration of uniaxial force sensor in recent years\cite{51-54}, and published guidelines for dynamic calibration of uniaxial force measuring devices in 2017\cite{55}. It has important reference value for dynamic calibration of multi-dimensional force sensor.

5.2.2 Dynamic coupling and decoupling

The interdimensional coupling interference between the output signals of multi-dimensional force sensor exists not only in the static measurement but also in the dynamic measurement. At present, most of the dynamic decoupling methods are based on the transfer function analysis, in which the decoupling network is simple and low precision, but the dynamic accuracy requirement for the force sensor is also urgently needed. Because of the error of measurement, interference and limitation of identification method, the dynamic coupling model is often inaccurate. In 2001, Song et al. proposed a dynamic decoupling method based on diagonal predominance compensation, which can be approximately decoupled by designing a steady compensator, but it doesn't reveal the dynamic decoupling relationship of multi-dimensional force sensor in theory\cite{56}. Combined with identification and niche genetic algorithm, Ding et al. established and optimized the dynamic decoupling network for calibration data. The decoupling network has certain robustness\cite{57}. In recent years, Wang et al. has studied the Blind Source Separation (BSS) method and applied it to the dynamic decoupling of multi-dimensional force sensors\cite{58}. In general, there are few researches on dynamic decoupling of multi-dimensional force sensor. However, with the wide application of multi-dimensional force sensors in the field of dynamic measurement such as haptic interaction, there is a growing need for dynamic decoupling of multi-dimensional force sensor.
6 Applications

6.1 Robotic applications

With the development of robotic technology, the application fields of robot have been greatly expanded, and its functions been significantly improved. Intelligentization has become the trend of robotics, and sensor technology is foundation of intelligent robot. As one of the most basic sensors of robot, multi-dimensional F/T sensor is mainly applied in the wrist and finger. Force and tactile measurement and feedback are indispensable when performing reliable and non-destructive manipulation of parts\(^5\). Consequently, multi-dimensional F/T sensors for intelligent robot have proliferated over the past few decades.

In 1992, a small cylindrical F/T sensor in robot manufacturing was studied by Little\(^6\). Park et al. developed a six-dimensional F/T sensor for an intelligent robotic gripper\(^7\). Luo et al. proposed a Stewart platform 3-dimensional force sensor with distinctive structure of ball joints for robotic fingers\(^8\). Wood et al. designed and fabricated a two-dimensional force sensor with parallel dual cantilever modules configuration to characterize the lift/drag force from a robotic insect\(^9\).

6.2 Biomedical and biomechanics applications

Accurate F/T measurements are required in many biomedical applications, such as MIS (minimally invasive surgery)\(^{64-65}\), diagnostics tools\(^{66,67}\), prosthetics and rehabilitation medicine. The surgeon exploits the finger palpation capabilities to characterize tissue hardness and to measure pulsating vessels\(^{65}\). During MIS, the applied force on tissue estimated by its deformation through visual feedback will lead to a serious limitation for the effectiveness of the operations. Consequently instruments capable of measuring and delivering F/T to the surgeon are required. Seibold et al. developed a Stewart platform based six-dimensional F/T sensor for MIS\(^{68}\), which is shown in Figure 17. The F/T sensor can measure manipulation forces at the instrument's tip. Dalvand et al. proposed an actuated modular force feedback-enabled laparoscopic instrument for robotic-assisted surgery\(^{69}\). The instrument is able to measure tip-tissue lateral interaction forces as well as normal grasping forces.

Biomechanics is a discipline that studies relationship between forces and motion, physiology, pathology of organisms. As a force measuring element, F/T sensor plays an important role in biomechanics. Krougliacof et al. developed 6 DOF force sensor for biomechanics and sports medicine based on Stewart platform\(^{70}\). Song et al. presented a novel three-axis force sensor for measuring the throwing forces of shot-put athletes\(^{71}\). Hybrid Assistive Limb was developed to assist the disabled in walking by Tsukuba University\(^{72}\). There are multi-dimensional F/T sensors in aforementioned mechanics instruments to achieve force measurement and force feedback.

6.3 Haptic interaction

Haptic interfaces enable person-machine communication through touch, and most commonly, in response
to user movements. Haptics refers to the capability to sense a mechanical environment through touch. Haptics also consists of kinesthesis, as well as the ability to perceive one's body position, movement and weight\(^1\). As illustrated in Figure 1, multi-dimensional force sensor is a foundational element for haptic interaction systems. Haptics applications such as computer interaction, teleoperation, teaching and training, games, and multimedia require a particular haptic device structure for various purposes\(^4\). Prattichizzo et al. designed a 3-DOF wearable device for cutaneous force feedback\(^3\). It consists of a static platform which placed on the back of the finger and a mobile platform which is responsible for applying forces at the fingertip. Force sensors on the mobile platform measure the normal component of the force applied to the fingertip. Hamid et al. developed a flexible endoscopic sensing module for force haptic feedback integration to measure the directional force\(^3\).

7 Conclusions

Multi-dimensional force sensors have been widely applied in the haptic interaction areas, which support the virtual reality and augment reality technology. Because the performance of multi-dimensional force sensor is largely dependent upon the mechanical structures of elastic beams, the design of elastic beam with new mechanical structure becomes main content of multi-dimensional force sensor research. Some typical mechanical structures of elastic beams of multidimensional force sensor are introduced, and the inter-dimensional coupling error is analyzed briefly. The static calibration as well as dynamic calibration of the force sensor is discussed in this paper. At last, we point out the developing trends and challenges of the dimensional F/T sensor research in future.

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