FlexTorque: a Novel Wearable Haptic Interface for Telexistence

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In order to present the contact and collision with environment to human operator arm in a natural manner, a novel haptic interface was developed. The key technology is that we use lightweight components (resulting in wearable design) and antagonistic DC-driven tendons. The latter allows not only generating the required torque but also compensating the excessive torque when presentation of rapidly raising torque is necessary.

Key Words: Teleoperation, Torque Display, Tactile Display, Safe Robot

1. Introduction

The devices for presentation of force/torque to the human arm are nowadays gaining increased interest in researches. The reason of this is a wide area of applications, such as, Virtual Reality, teleoperation, physical rehabilitation, etc. The paper focuses on torque feedback device for the teleoperation system TeleTA (Teleoperation system with wearable Tactile display on the operator arm surface providing Awareness about slave robot collision) designed by us to achieve high level of maneuverability of robot arm in unstructured dynamic environment and to perform cooperative tasks with humans in a safe manner. We announce several distinctive contributions in this paper. New remote robot and sensory system for the operation in cluttered environment were developed. Distributed optical joint torque sensors and local admittance controllers endow our robot arm with the distinctive capability of safe interaction with surroundings along entire manipulator surface (including joints) [1]. The applied force vector can be calculated from the values of joint torques and contact point coordinates.

Master side (Fig. 1(a)) includes exoskeleton robot arm with 6 DOF (Fig. 1(b)), tactile display BraTact aimed at presenting the cutaneous stimulation when collision with object is detected, and torque display FlexTorque for generating kinesthetic stimuli. When operator moves his arm, its position and velocity in Cartesian space is measured by optical encoders embedded into joints. The orientation of the human elbow is controlled by the tilt sensor. The calculated coordinates of the master arm tip are transmitted to the slave robot control system that computes the inverse kinematics. Master manipulator has a gravity compensation system, so that operator does not experience gravity load during teleoperation.

Teleoperated robot arm has 4-DOF: Roll, Pitch, Yaw joints of a shoulder, and Pitch joint of an elbow (Fig. 1(c)). Each joint is equipped with optical torque sensor directly connected to the output shaft of harmonic drive [2].

Proposed sensory system of slave robot (tactile skin to detect contact point and torque sensors distributed into each joint for measurement of applied force) patterns on the human tactile system. Our sense of touch can be separated into kinesthetic and coetaneous. Kinesthetic stimulations, produced by forces exerted on body, are sensed by mechanoreceptors in the joints, tendons, and muscles enabling us to estimate forces being applied to body [3]. On the contrary, mechanoreceptors in the skin layers are responsible for cutaneous stimulation sensation that enables stimuli localization.

The robot arm is covered with Kinotex tactile sensor measuring the pressure intensity through amount of backscattered light falling on photodetector [4]. The sensitivity, resolution, and dynamic range of this artificial skin are comparable to those of a human. It should be mentioned, however, that it is useful only for contact area and contact point recognition (cutaneous channel). Applied force sensitivity is very low due to large hysteresis, high non-linearity of the output, and limited sensing range. The task of load measurement is accomplished by the developed optical torque sensors aimed at torque measurement in wide range with high accuracy (kinesthetic channel).

In order to recognize the contact region, we employed the watershed algorithm, an image processing segmentation technique that splits an image into areas based on the topology of the image [5]. The accurate estimation of the contact point can be obtained by computing the center of gravity of the contact pattern \(c(x_1y_1)\) of the neighborhood \(\Omega\) by:

\[
c(x_1y_1) = \frac{\sum_{x,y \in \Omega} x f(x,y) \sum_{x,y \in \Omega} y f(x,y)}{\sum_{x,y \in \Omega} f(x,y)^2},
\]

Fig. 1 Robot teleoperation system TeleTA


1A1-B01(1)
where $f(x,y)$ is the pressure intensity level of the taxel $i$ with coordinates $(x,y)$.

In order to implement realistic haptic interaction with environment (pushing and contacting the object, collision) and haptic communication with human beings (e.g., handshaking), the force feedback is required. The aim of our research is the development of wearable haptic display which can present cutaneous and kinesthetic feedback to the operator’s arm.

In the remainder of the paper we describe the current technologies of torque feedback systems, design of torque display FlexTorque, and development of ergonomic tactile display BraTact for presentation of contact location and object properties.

2. Current Master Arm Systems

Most of the force feedback master devices are similar in sizes to slave robot and are equipped with powerful actuators. Such systems pose dangerousness for human operator and in case of failure during bilateral control can harm human. In the last years there have been several attempts to make the force feedback devices more compact, safe, and wearable.

In [6], an exoskeleton-type master device was designed based on the kinematic analysis of human arm. Pneumatic actuators generate torque feedback. The authors succeeded in making the lightweight and compact force reflecting master arm. However, the force-reflection capability of this device is not enough to present contact forces effectively. Moreover, pneumatic actuators have large time delay, complicated control, and limited workspace.

An artificial pneumatic muscle-type actuator was proposed [7]. Wearable 7 DOF robotic arm providing high joint torques was developed. Robotic arm uses parallel mechanisms at the shoulder part and at wrist part similarly to the muscular structure of human upper limb. It should be noted, however, that dynamic characteristics of such pneumatic actuator possess strong nonlinearity and load-dependency, and, thus, a number of problems need to be resolved for its successful application. The weight of 4 kg and cumbersome structure significantly degrade the initial concept of human-friendly and wearable design. Special fail-safe control is needed due to high power of adopted pneumatic actuators.

3. Design of Torque Display FlexTorque

In conventional exoskeleton master arms, bulky actuators are placed near the joints and are connected by rigid heavy links [8]. Such configuration causes overloading of the human muscles while object manipulating. Desktop-type force-feedback devices (e.g., PHANTOM) enable to generate force only at the human hand, and have narrow workspace.

In order to achieve human-friendly and wearable design of kinesthetic display, we analyzed the amount of torque to be presented to the operator’s arm. Generally, there are three cases when torque feedback in needed. The first case takes place when haptic communication with remote human needs to be realized. For example, the person handshakes the slave robot and joint torques must be presented to the operator. Such interaction causes very small joint torques (in the range of 0-1.5 Nm). The second situation takes place when slave robot transports heavy object. Here, the torque values are much higher than in previous case and torque magnitude depends on the load weight. However, continuous presentation of high torques to the operator will result in human muscle tiredness. We argue that downscaled torque indicating direction of the force might be very informative. The third and the worst case of contact state in term of interactive force magnitude is collision. It is obvious that high torque will be produced when robot collides with moving object. In indoor environment, robot arm collides with the fixed objects more frequently. The result of such collision is immediate discontinuation of the robot arm motion. Therefore, the power of torque display must be enough to fixate the operator arm.

The idea behind novel torque display FlexTorque is to reproduce human muscle structure, that allows us to perform dexterous manipulation and safe interaction with environment in daily life. The muscle with tendon in series acts like a rope pulling on a lever (Fig. 2).

![Movement of human limbs is produced by coordinated work of muscles acting on skeletal joints](http://example.com/muscles.png)

Because muscles pull but cannot push, hinge joints (e.g. elbow) require at least two muscles pulling in opposite direction (antagonistic muscles). The torque produced by each muscle at a joint is the product of contractile force ($F$) and moment arm at that joint ($d$). The net torque is the sum of the torques produces by each antagonistic muscle.

The structure of the developed torque display FlexTorque is presented in Fig. 3. FlexTorque is made up of two DC motors (muscles) fixedly mounted into plastic Motor Holder unit, belts (tendons), and two Belt Fixators. The operation principle of the haptic interface is as follows. When DC motor is activated, it pulls belt and generates thus the flexor torque. The oppositely placed DC motor generates the extensor torque. Therefore, the couple of antagonistic actuators produce a torque at operator elbow joint. The position of the operator’s arm, when it undergoes flexor torque, is shown in Fig. 4 ($\theta$ stands for angle of forearm rotation in relation to upper arm).
Let us consider the calculation procedure of the required torque value. The layout of the forces and torques applied to the forearm under flexor torque is given in Fig. 5. The tension force $F_t$ of the belt can be derived from:

$$F_t = \frac{T_m i}{r}$$

(2)

where $T_m$ is the motor torque, $i$ is the gear ratio, and $r$ is the shaft radius.

The net torque $T_n$ acting at the elbow joint is calculated as:

$$T_n = F_id_f = F_id_f \sin(\alpha)$$

(3)

where $d_f$ is the moment arm.

In the case of collision, the limb must be at rest. The net torque produced by the muscles is opposed by another equal but opposite torque $T_{load}$. This torque is caused by gravitational forces acting on the human forearm and upper arm, and inertial load.

The essential advantage of the structure of FlexTorque device is that heaviest elements (DC motors, shafts, and pulleys) are located on the part of upper arm near to shoulder. Therefore, operator’s arm undergoes very small additional loading. The rest of components (belts, belt fixators) are light in weight and do not load the operator’s muscles considerably.

4. Development of the Ergonomic Tactile Display BraTact

In order to deliver the sense of object touch to the operator, the force-feedback devices (generating kinesthetic stimuli) and tactile-feedback system (evoking cutaneous stimuli on local area of the skin) are widely applied. When it comes to the contact presentation on the human arm, tactile displays are preferable ones. They can convey contact cues [9], direction, and distance information [10].

It can be seen from the papers presented above that, typically, the huge amount of actuators are arranged in regular grid pattern. It should be mentioned here, that heavy tactile display placed on the arm surface degrades the mobility and increases joint muscle loading. Therefore, our objective was to find out the approach to effective presentation of tactile information.

Several attempts were made to explore the human tactile patterns for effective communication with mobile devices [11], [12]. Chen et al. [13] examined the human ability to localize a single vibration source on dorsal and volar sides of the forearm near wrist. For the experiments a 3-by-3 tactor array was placed on the dorsal and volar parts of the wrist, respectively. An important finding was that on average only 4 tactor locations could be correctly identified on both sides of the wrist.

The developed tactile bracelet BraTact (Bracelet with Tactors) incorporates six vibration motors with holders linked by elastic band. Proposed shape takes advantage of the facts that we already used to wear bracelet-shaped watches.
and accessories, and that such shape of the tactile display can fit to the human arm of different sizes. To enhance the localization ability, we arrange the tactors in a zigzag pattern (Fig. 6).

![Figure 6 Tactile display BraTact](image)

The inner surface of the holder has concave profile to match the curvature of human arm surface. The designed tactile bracelet is shown in Fig. 7.

![Figure 7 Tactile bracelet](image)

The small flat coreless vibration motors FM34F with diameter of 12 mm and thickness of 3.4 mm produce tactile stimulation on human skin. The control signal is generated by PC (Fig. 8).

As it follows from the graph of vibration motors FM34F motor characteristic, the relationship between voltage (current) and frequency is essentially linear. Therefore, the level of current in tactor circuit corresponds the level of vibration. The tactile display was connected to the Motor Driver Unit controlled by the signals from D/A board.

![Figure 8 Control system of BraTact](image)

5. Conclusion and Future Work

A novel haptic interface FlexTorque aimed at presentation of interactive forces to the operator was developed. The FlexTorque can not only present torque but also produce desired stiffness at the joint. For example, while handshaking our joint stiffness adapts to the stiffness of the partner arm. As slave robot enables changing the joint stiffness by means of variable admittance control, we can achieve natural haptic human-robot communication on the remote side. At the same time, this stiffness can be presented to the operator by FlexTorque.

In near future, we plan to integrate two displays BraTact and FlexTorque in order to outperform conventional haptic displays in quality of haptic information presentation. The BraTact display will deliver cutaneous information about contact point location and local pressure, while FlexTorque will provide the kinesthetic channel (torque applied at the joint). Such system can present the haptic interaction of the slave robot with environment to the operator in a very natural and realistic manner.

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References


