HAPTIC INTERFACES FOR ROBOTIC ARM CONTROL: PSYCHOPHYSICAL FOUNDATIONS, DEVICE EVALUATION AND CONTROL CONCEPTS

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ABSTRACT: Haptic feedback devices artificially reproduce the sense of touch, allowing human operators to perceive forces, vibrations and contact information exchanged with real or virtual objects. This paper reviews the theoretical background required for the design and selection of haptic interfaces used to control robotic arms. The classical psychophysical methods used to quantify human touch perception – the method of limits, the method of constant stimuli and adaptive (staircase) procedures – are presented together with the concept of the just noticeable difference (JND). Haptic devices are classified into kinesthetic and tactile categories, with emphasis on grounded force-feedback (GFF) devices, which remain the most mature and most widely used haptic technology. The evaluation criteria proposed for GFF devices and their six key attributes are discussed, together with actuation and control concepts – PID and fuzzy-logic control and master–slave architectures – relevant to robotic-arm teleoperation. Current perspectives on integrating haptic technology with virtual reality and artificial intelligence are also outlined. The conclusions reflect on the feasibility of using haptic feedback to improve precision, safety and intuitiveness in human–robot interaction.

Keywords: haptic devices, force feedback, robotic arm control, psychophysics, teleoperation, human–robot interaction

1. INTRODUCTION

Haptics is the science and technology of touch. Engineers, designers and researchers active in this field try to recreate the sense of touch by means of haptic interfaces that can sense a physical quantity from the user (movement, force), act physically on the user through an actuator, and connect what is sensed with the resulting action through a fast feedback loop.

The usefulness of such interfaces is broad. They can increase the human capability to interact with the real world and, in extreme cases, replace lost limbs. Haptic devices also assist remote interaction in dangerous or complex environments, such as maintenance in space, surgery, or the cleaning of contaminated areas. With these interfaces, operators can perform complex tasks with higher accuracy and a reduced risk of accidental damage. Haptic interfaces are also used to create more immersive virtual content through sensory feedback, and are suitable for a large number of applications: surgery, medical rehabilitation, teleoperated robots, education, the study of human perception, virtual-reality entertainment and the communication of emotions.

Different haptic interfaces are designed through a process that starts with understanding tactile perception and the quality of the feedback that must be delivered. In the next stage, the haptic technology is established and the hardware settings capable of reproducing the selected or designed haptic sensation are configured. Only at the end is the haptic device integrated with the user(s), who must understand the key aspects of this process.

Among the five human senses, hearing and vision are centralized, act at a distance and cover a large area, while the tactile sense is interactive, multimodal, localized, distributed and private. It has two sub-modalities: the tactile or cutaneous sub-modality, whose sensor parameters provide information about pressure, vibration, temperature and contact, and the kinesthetic or proprioceptive sub-modality, whose sensor parameters provide information about position, orientation and force. In practice, both sub-modalities are usually encountered together, and the skin – through the many separate nerve types that register pain, light or noxious touch, pressure, warmth or cold – is the main organ of the tactile sense, allowing the perception of physical characteristics such as shape, hardness, texture and weight.

2. METHODS FOR STUDYING HUMAN TOUCH PERCEPTION

To study human perception, researchers rely on an established set of procedures known as psychophysical methods. Their origins lie in the 19th century, with Ernst Weber's first experiments aimed at quantifying human perception of touch and light, later extended by Gustav Fechner. Psychophysics investigates, quantitatively, the mechanisms involved in the detection and processing of sensory information: the physical properties of a signal in the real world are captured by sensory receptors (e.g. the eyes or the tactile receptors in the skin), whose activity is transmitted to the peripheral and central nervous systems, where it is evaluated by metacognitive processes before the stimulus is reported.

The just noticeable difference (JND) is the amount by which a physical stimulus, such as light or force, must be changed for people to detect that a change occurred; it is captured by the psychometric function, which describes the probability of detecting differences in a physical stimulus. Jones and Tan [4] describe three classical psychophysical procedures used in haptic research, summarised in Table 1.

Table 1. Classical psychophysical methods

Method	Principle
Method of limits	Ascending/descending series; threshold = mean transition point. Fast, but subjective.
Constant stimuli	Predefined stimuli, random order, 10–20 repetitions per pair. Robust, but long.
Adaptive (staircase)	Intensity adapted to previous responses (e.g. 3-down-1-up). Fast, narrow band.

Using the method of constant stimuli, researchers have estimated key parameters of grounded force-feedback (GFF) devices; for example, the minimum force resolution perceivable by a user interacting with a GFF device is about 7% of the reference force, and this value is largely independent of the reference stimulus. The adaptive (staircase) method reduces experiment duration and participant fatigue, but it does not estimate the full shape of the psychometric function, some haptic devices cannot implement the constant steps it requires, and participants may anticipate the staircase logic or exceed the predefined stimulation limits.

3. CLASSIFICATION AND EVALUATION OF HAPTIC DEVICES

3.1. Classification of haptic devices

Haptic devices are generally classified into kinesthetic devices, which primarily stimulate muscles or skin, and tactile devices, which primarily stimulate the skin. Kinesthetic devices include grounded force-feedback devices – stationary robots controlled by a human operator – and ungrounded devices, such as exoskeletons, force gloves or wearable devices mounted on the user's body, which deliver kinesthetic force without being grounded. Tactile devices include vibrotactile devices (e.g. wearable arrays of vibration actuators, mobile phones), finger-based devices that press or stretch the skin to convey contact information, surface-haptics devices that render friction and texture on a touchscreen, and mid-air (ultrasonic) devices that stimulate the hand using ultrasound beams.

3.2. Grounded force-feedback (GFF) devices

The grounded force-feedback device is the first and most mature type of haptic technology and remains the most widely used to date; it paved the way for portable and ungrounded devices. A GFF device is a robot mounted on a stationary surface that exchanges kinetic energy with the user, usually through an end-effector that measures and modulates the position, orientation or torque applied by the user, since the resulting force is felt mainly through the muscles connecting the user to the surface. Development of force-feedback devices began around 1990 within robotics; since then, haptics has evolved into its own research field, and hundreds of GFF devices – with a wide range of capabilities suited to different applications – have been catalogued in open, community-maintained databases such as Haptipedia, building on early surveys of haptic-interface research such as the one carried out at McGill University [3].

3.3. Evaluation criteria for GFF devices

In 1994, Massie and Salisbury [7] proposed three criteria for evaluating force-feedback devices: (1) free space should feel free – the friction, weight and inertia of the device should be as close to zero as possible, so the user perceives the virtual environment rather than the device itself; (2) solid virtual objects should feel rigid – haptic research suggests a stiffness of at least 20 N/cm is required for a virtual surface to be perceived as a solid wall, with values above 100 N/cm improving the perception of an immovable wall; and (3) virtual constraints should not saturate easily – the maximum output power of the device must be high enough that users do not exceed it while interacting with rigid virtual objects.

In practice, additional criteria are used to evaluate and select a GFF device for a given application: ergonomic motion, a larger workspace, more degrees of freedom, user comfort, dexterity within the virtual environment, precision of inputs and outputs, and higher position/force sensing and output resolution. Cost, ease of construction and ease of maintenance can also play an important role. These performance criteria are not strict rules and their desirability depends on the application: they are appropriate for teleoperation and virtual-reality applications, but for specific medical applications requiring flexible and soft interaction, a low-stiffness, low-output device may be preferable instead.

3.4. Key attributes of haptic devices

Over the last three decades, haptic engineers have designed grounded force-feedback devices with a wide range of capabilities. Although the literature lists many engineering and usage attributes (54 are catalogued in Haptipedia), experts have identified six key attributes used to classify GFF devices, summarised in Table 2: (a) how the device connects to the user's body (body part and end-effector, e.g. handle, pinch handle, joystick, mouse, stylus or thimble); (b) its range of motion, described through degrees of freedom and workspace; (c) its mechanical structure (peak force, serial/parallel/hybrid structure); (d) the versatility of its features, from general-purpose research prototypes to specialised medical, educational or entertainment devices, and from commercial devices – more robust, reliable and higher-resolution, but expensive – to open-source, do-it-yourself devices, which are cheaper and easier to customise but usually lower in resolution and fidelity; (e) unique engineering attributes, such as magnetic-levitation actuation, which offers high output power, high resolution and high transparency but a small workspace and no friction rendering, electrostatic or mechanical brakes, which are safe but harder to control, robotic totems (e.g. joystick- or mouse-like end-effectors), which are safe and offer a large workspace but are complex to build and limited in output force, and admittance-type devices, which measure force and output position – unlike the majority of GFF devices, which are impedance type – offering high stiffness at a higher cost; and (f) the complexity of construction and use, which generally increases with the number of degrees of freedom and the range of motion, from simple, low-DoF, 3D-printable serial devices to complex 6–7 DoF parallel or hybrid devices requiring machined metal parts.

Table 2. Key attributes used to classify GFF devices

Attribute	Description
Body attachment	End-effector: handle, pinch grip, joystick/mouse, stylus/thimble
Range of motion	Degrees of freedom and workspace size
Mechanical structure	Peak force; serial, parallel or hybrid structure
Versatility	General vs. specialised; commercial vs. open-source (DIY)
Unique attributes	Magnetic levitation, mechanical brakes, totems, admittance type
Complexity	Increases with DoF count and range of motion

4. ACTUATION AND CONTROL CONCEPTS FOR ROBOTIC ARMS

Developing robots with superior capabilities requires an optimal combination of a large workspace, high stiffness, high execution speed and high positioning accuracy. Because of these advantages over serial robots – higher stiffness, better accuracy, higher speed and acceleration, and a better ratio between robot mass and payload – parallel robots currently represent the frontier of robotics research worldwide.

Several actuation and control techniques (control algorithms) are used for robots: classical solutions, such as proportional–integral–derivative (PID) control, and advanced solutions, such as fuzzy-logic control, adaptive PID, and model-based adaptive-predictive algorithms. The identification algorithms most often implemented in applications are based on the least-squares method or on neural networks; with adequate control algorithms, the accuracy of parallel robots can be further improved.

A PID controller is a generic feedback-loop control mechanism, widely used in industrial control systems, which computes an error – the difference between a measured process variable and a desired reference value – and attempts to minimise this error by adjusting the control input used to drive the process:

$$u(t) = K_p e(t) + K_i \int_0^t e(\sigma) d\tau + K_d \frac{de(t)}{dt} \quad (1)$$

where (u(t)) represents the control signal applied to the actuator, while (e(t)) denotes the tracking error between the desired reference signal (r(t)) and the measured system output (y(t)), defined as (e(t)=r(t)-y(t)). The proportional, integral, and derivative terms provide complementary contributions to the control action. The proportional gain (K_p) determines the response to the instantaneous error and generally increases the responsiveness of the system. The integral gain (K_i) determines the contribution of the accumulated error over time and helps reduce or eliminate steady-state error. The derivative gain (K_d) determines the response to the rate of change of the error and can improve system damping and transient response. Thus, the PID controller combines information about the current error, its accumulated history, and its rate of variation to generate an appropriate control signal.

A fuzzy-control system is a control system based on fuzzy logic, a mathematical system that analyses analogue input values in terms of logical variables taking continuous values between 0 and 1, in contrast to classical (digital) logic, which operates on discrete values (true/false); fuzzy logic is also widely used to control machine tools.

Depending on the source of information, one defines the robot’s operating mode, its basic functional characteristics, the structure of the control algorithms, the way information is processed (real time or not), and the relationship between the robot and the user, which may determine autonomous operation or operation in association with the user, as in teleoperation systems. A robot consists of two parts: an information-processing unit – a hardware–software complex that receives operating instructions, measurements of the operational unit’s state and observations of the operating space, and decides, according to the established control algorithms, how the operational unit should act – and an operational unit, corresponding to the robot itself, comprising its mechanical structure and associated actuation system, which acts on the operating space using the energy supplied by the source and reacting appropriately to external signals.

The typical robot architecture follows the classic master/slave configuration, with two modules: the user console (master), which typically includes gripping elements (levers) and may include a vision system and/or voice-command components, and the robot (slave). When the user interacts with the robot through a haptic device to move instruments, the forces and torques generated by the user’s hand are sensed by a force/torque sensor and transferred to the robot. The interface must allow the user to operate the robot as easily as possible, without being overloaded with information that could distract the user’s attention.

5. PERSPECTIVES IN HAPTIC DEVICE DEVELOPMENT

Engaging the sense of touch in human–computer interaction is expected to improve robotic control, physical rehabilitation, education, navigation, communication and even online shopping – including mobile and handheld tactile-display scenarios beyond stationary GFF devices [6]. Haptic technology can be used in touch-perception experiments through GFF devices, in the study of haptic signals, and in haptic experience design (HaXD) [8].

Humans integrate visual and haptic information in a near-statistically-optimal fashion [2], which is directly relevant to the realism achievable when haptic feedback is coupled with virtual reality. Understanding tactile and haptic illusions [5] further informs the design of devices that must remain perceptually consistent under multimodal stimulation.

Current perspectives in the development of haptic devices concern their integration with virtual reality and with artificial intelligence, including neuroscience-oriented approaches to investigating the causal role of sensory manipulation in perception [9], and the study of workspace and object-surface texture rendering with haptic devices [1].

6. CONCLUSIONS

This theoretical review has examined the scientific background required for the design and selection of haptic devices intended for robotic-arm control: the psychophysical methods used to quantify human touch perception, the classification of haptic devices, the evaluation criteria and key attributes of grounded force-feedback devices, and the actuation and control concepts – PID and fuzzy-logic control, master–slave architecture – used in robotic-arm teleoperation.

Grounded force-feedback devices remain, at present, the most feasible solution for haptic control of robotic arms, owing to their technological maturity, their well-established evaluation criteria and their compatibility with the classical and advanced control algorithms already employed in the control of parallel robots. Combining rigorous psychophysical calibration with the GFF evaluation criteria discussed above is considered a realistic way to improve the precision and safety of teleoperated robotic arms. The long-term feasibility of further improvements will depend on progress in artificial-intelligence-assisted control and in virtual-reality-integrated haptic rendering, both of which are still maturing but show strong potential to reduce the cost and complexity of future haptic devices used for robotic-arm control.

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