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DESIGN ISSUES AND REQUIREMENTS OF A GENERAL PURPOSE DESKTOP HAPTIC INTERFACE

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ABSTRACT
Haptics is a complement to visual and auditory perception for a more complete experience of being in an environment, be it real, remote, or virtual. Haptic interface allows users to interact with the environment through touch or manipulation. Many of these devices have been built in the recent years. This paper reviews the design requirements of a haptic device in pursuit of a haptic interface that provides a more realistic sensation to the user. Two popular haptic devices: the PHANToM and the DELTA haptic devices are discussed.

Key Words - Haptics, Man-Machine Interface, Light Inertia Robot, Design Requirements.

I. INTRODUCTION

Haptics deals with the form of sensory information that is acquired through the touching or handling of an object. This is generally divided into *cutaneous* and *kinesthetic* sensations [1]. *Cutaneous* sensation is can be thought of as the superficial sensibility associated with the skin. This includes pressure, vibration, slight displacement and temperature. *Kinesthetic* sensation or *proprioception* responds to motions and forces exerted by the interaction of the body with the external environment. This is also considered as “deep sensing” associated with internal receptors in muscles, tendons and joints as opposed to “superficial sensing” associated with the skin as in cutaneous sensation [2].

This paper reviews design criteria of a haptic interface that deals mainly with kinaesthetic sensation. These devices generally come in the form of a robotic manipulator, mostly closed-chain mechanisms or at least hybrid mechanisms, such as [3,4,5,6,7,8]. Spherical geometry has also been explored taking advantage of its uniform dexterity throughout the workspace [9]. Other variations are also available, such as the Magnetic Levitation Device [10, 11].

II. DESIGN CRITERIA

Haptic interface presents a difficult mechanical design problem, as it is required to be light and backdrivable, as well as being able to provide high stiffness. As haptic interface is designed to display tactile and force feedback at the end-effector, the fidelity of force feedback is of utmost importance. Structural transparency is required so that the user should feel only the dynamics of the mechanism being represented and not that of the structure of the haptic device's [12]. The primary requirement for the design of a haptic interface can therefore be summarized as “to be able to display a broad range of impedance” [13]. This can be achieved through many design parameters of the mechanism.

2.1. Backdrivability

Backdrivability is a very important criterion in a haptic device. The haptic interface must be able to move freely while in free motion, exerting virtually zero resistance force to the user, representing “no-contact” situation with the environment. The users feels no resistance and the haptic device seems weightless. Only certain designs, such as [7], do not require backdrivability. The device, by Yoshikawa, uses a ring with IR sensors inside which the user places his finger. The IR sensors detect motion of the user’s finger. The ring is actuated by a manipulator to move with the user's finger and only touches the finger at the appropriate moments when force is to be exerted onto the finger. This mechanism is under motion control at all times. Other haptic interfaces generally require the user to hold onto the end-effector of the device, and therefore require backdrivability. This effort includes removing backlashes and reducing friction where possible: by actuating the joints of the mechanism through direct drive or cable drive (no gears), and roller bearings in all the passive joints.

2.2. Inertia Consideration

As the haptic device should display the desired force and not the dynamics of the haptic device, most of them are designed to be as light as possible. Choice of material such as aluminum tubes, carbon fibre links, and choice of hardware such as low inertia motors help in this aspect. Also they are to locate heavy components such as the motors and counterweights to be at the base of the mechanism.

Configuration of the mechanism plays a large role in reducing the effective mass of the mechanism. It is desired to have all the motors and heavy components to be at the base of the mechanism and that these heavy components do not move with the joints.

Many parallel mechanism designs satisfy this property. Their actuators at the base of the mechanism control the motion of the end-effector through its light parallel linkages [4,12,13,14]. A popular haptic device based of the delta mechanism [4] provides 3DOF motion (or force) feedback. However, to create the 3 additional (orientation) degrees of freedom, an active wrist mechanism is added at the end-effector. The mass of this attachment is now reflected at the end-effector.

This shows the advantage of a parallel mechanism over its serial counterpart in terms of transmission of motion and forces to the end-effector. Each actuator of a parallel mechanism is connected to the end-effector either directly or via passive joints. This allows all the actuators to be located at the base of the mechanism and these motors do not move together with other joints. In serial manipulators, it is also possible to locate all the motors at the base of the manipulator such as in the robot design by Khatib [15]. However, it is not as straight forward as in a parallel mechanism; because in serial manipulators, one joint is built on top on another. Motor for joint $i+1$ therefore moves (rotate or translate) with joint i. To locate the motor of joint $i+1$ so that it is fixed stationary to the base of the mechanism, a coupling effect will surface where joint $i+1$ will also move when only joint i is driven.

While effort can be made to lower the effective mass of the mechanism [16], it is also important to have **isotropy** in the dynamics of the device. It is desired that the user feels a uniform amount of effort to move the haptic interface in all directions, such as shown by [17] for general manipulators. This uniformity is reflected on the condition number of the operational space inertia matrix Λ. A condition number of 1 shows that the major and minor principal axes of the N dimensional inertia ellipsoid are of equal length, which reflects equal effective mass at the end-effector in all directions [18]. N is the number of task DOFs the mechanism possesses. This property should also hold consistently throughout the workspace, or at least uniform in as much of the workspace as possible.

It should be noted that the effective mass analysis for the translational and rotational motion should be done separately. [18] is an extension of the work by Yoshikawa on the *manipulability* of manipulators [19].

It is obvious that parallel manipulators are capable of better stiffness and larger force than serial manipulators. It is also known to have a more even inertia distribution in all directions than serial manipulators. Simple serial manipulators possess varying degree of isotropy in its entire workspace, with singular configurations being the worst because the end-effector no longer possesses the ability to move in its full DOFs. At these configurations, the condition number of Λ is infinity. A parallel manipulator can be thought of as several serial manipulators with a common end-effector. The dynamics reflected at the end-effector is the sum of the dynamics of all the individual 'arms' – from the ground to the end-effector. When the 'serial arms' are set in a configuration where the direction of a major principal axis of one arm as much as possible complements the minor of another, then the resulting ellipsoid for the reflected mass of the parallel mechanism can be made closer to isotropy than its individual serial arms.

2.3. Force and Mechanism Bandwidth

It is generally accepted that the maximum limit to a useful impedance range is the stiffness required to counteract a reasonable maximum human hand force while the minimum is the impedance below which it is too small for human hand to detect. Force magnitude at the end-effector is affected by the choice of motor and the kinematic design.

In the design effort, we normally deal with mechanism bandwidth, control bandwidth, and hardware (sensor and actuator) bandwidth. Mechanism bandwidth relates to the natural frequency of the mechanism and is often the limiting factor among the three categories of bandwidth.

Haptic tasks can be categorized based on its frequencies, with kinaesthetic related tasks being in the lower frequency category (such as touching the wall, object surface) and tasks closer to tactile sensation in high frequency category (such as surface roughness.) The desktop haptic interfaces in our discussion cater for kinaesthetic perception. However, mechanism capable of high frequency response is still desired. A soft or spring-like surface may not require such high frequency response, but to display realistically a stiff environment, a high frequency response is still necessary so it would not dampen the feedback.

Light inertia and distribution of mass in the mechanism is the major contributing factor to frequency of the mechanisms. These devices, however, would be more difficult to control in a stable and robust manner as it is sensitive to noise. This is covered in Section 3.

2.4. Workspace Consideration

To the other side of the spectrum of the design criteria is the workspace of the haptic interface. There is always a trade off between being able to display a broad range of impedance - as all the other design criteria we discussed above - and being able to provide a large workspace and good dexterity. Most of the time, workspace and dexterity are given less weight as haptic interfaces are designed for a specific application or for probing actions in a small region.

Currently, the popular solution to providing a larger workspace is to shift the point or the workspace of interest to a new location or to combine the interface with locomotion interface such as a treadmill, as implemented in [20, 21].

While there are ways to scale and to shift base frames to help overcome workspace limitation, dexterity is entirely dependent on the kinematic design of the mechanism. This is where parallel mechanism has significantly less advantage over its serial counterparts. As force display is the main purpose of haptic interface, it can be seen that most devices available today subscribed to the use of parallel mechanisms. SensAble PHANToM is the closest to a serial manipulator as joints 2 and 3 are built on top of joint 1. However, joint 2 and 3 form a close-chain mechanism. Therefore this device is often described as a hybrid mechanism.

III. CHALLENGES IN CONTROL

Control challenges are inseparable from the design of a good haptic device. Control of a haptic device is somewhat similar to the control of conventional robot manipulators, but is more challenging as a haptic device is designed to have smaller inertia and faster response.

The control objective of a haptic device is to provide an authentic, safe and stable force feedback to an operator. With light inertia, a haptic device is capable of a wider bandwidth of response. This means it is more susceptible to noise and disturbance that conventional manipulators, such as the PUMA560, which is heavy enough to dampen some of the disturbances or even certain unstable region in its response.

3.1. Dynamic Model

In a motion controlled robotic manipulator, for example, in a pick and place task where only motion is considered, high level kinematic control such as RMRC (resolved rate motion control using velocity commands) with PID control is often utilized.

However, in the control of a haptic device where the fidelity of force displayed at the end-effector is of utmost importance, the dynamic model of the mechanism is required [22]. Control should take into consideration the dynamics of the haptics device and compensate for it.

3.2. Friction

With light inertia of the mechanism, the effect of friction becomes more apparent compared to conventional robotic manipulator. Precise control of a haptic device in the presence of friction-related effects is a challenging task. Friction is one of the major limitations in achieving high precision motion control. It has many diverse aspects giving rise to control problems such as steady state errors, tracking errors, limit cycles, and stick-slip. Compensating for friction, if not done properly, may give rise to stability problems. Many efforts have been made to minimize friction effects mechanically, like cable driven haptic devices. However it is very difficult to totally eliminate it mechanically. Therefore, effective compensation for friction within the control algorithm is often necessary,. For example, in [23], a force feedback control strategies including a feed-forward friction compensation based on joint torque have been proposed and are evaluated through experiments.

3.3 Noise from Backward Difference for Velocity Estimation

Advanced control algorithms on robotic manipulators have been accorded a considerable degree of attention. Although the designs of many of these controllers are elegant, their implementation is hindered by the fact that they often require the measurements of both link position and velocity. In practice, most robot manipulators are only equipped with link position sensors. Measurement of link velocity is possible, but the measurements are often contaminated by noise, which will reduce the bandwidth of a robotic system. This problem has been partially solved by resorting to “filtering” (e.g. a backwards difference algorithm used in conjunction with a low pass filter) of the joint position information to estimate the link velocity. This filtering method causes tracking delay. In a robotic manipulator that is intended as a haptic interface, this method will erode the benefits from the effort of designing light inertia mechanism to display fast and realistic force response.

To overcome this drawback, we developed an observer-controller for operational space trajectory tracking without velocity measurements, simulation results done on a three-link robot showed that the proposed observer-controller could achieve higher tracking accuracy than the conventional computed-torque PD controller using filtered velocity. And the experimental results done on PUMA 560 robot manipulator verified its better position tracking performance over the same controller but employing filtered velocity [24]. This control scheme may be a suitable candidate for haptic device motion and force control.

IV. EXISTING SYSTEMS

This section presents several examples of popular haptic devices available today. First in the examples are SensAble PHANToM [25] and the DELTA Haptic device [26].

PHANToM is of a hybrid configuration. This design is unique because most devices in the market today concentrate on parallel mechanism. Joint 2 and joint 3 of PHANToM are in parallel to each other, but they are in series with joint 1 (see Figure 1.) Joint 2 drives the upper link while joint 3 drives the lower link A spherical wrist is attached to the end-effector to provide the rotational 3DOFs.

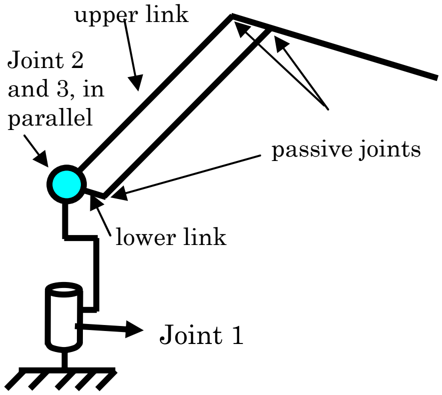

Figure 1. The schematic of the first 3DOFs of PHANToM

DELTA is built based on the Delta mechanism by Clavel. It is a parallel mechanism capable of

3DOF (translation in 3D). Rotational DOF is also provided by attaching a wrist module at the end-effector (Figure 2.)

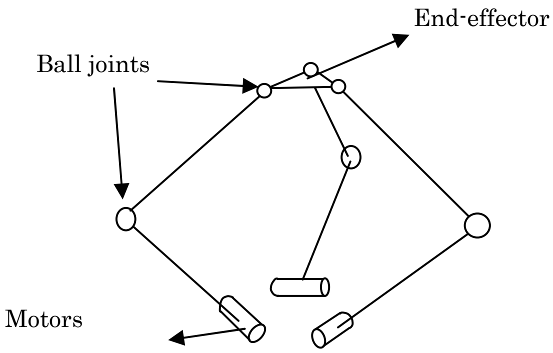

Figure 2. Schematic of a 3DOF Delta mechanism. For the 3DOF rotation, a wrist module is attached to the end-effector.

4.1. Workspace

Although it is difficult to compare the two structures, it can roughly be determined that for a smaller footprint and size of the device, PHANToM provides a larger workspace. Because of the difference in sizes, Table 1 also shows a normalised workspace volume divided by footprint to better show the advantage of serial element in the configuration of the mechanism in terms of workspace.

	PHANToM	**DELTA**
Workspace (translation)	195x270x375 mm	Cylinder diameter 360mm x L 300mm
Workspace volume	19.7 litres	30.5 litres
Workspace Volume/footprint	2.39	1.09
Workspace (Rotation)	About 300° for each axis	+/- 20° for each axis

Table 1. Workspace comparison between PHANToM 1.5/6DOF model (hybridmechanism) [25] and DELTA 6 DOF model (parallel mechanism)[26].

4.2. Force and Mechanism Bandwidth

What DELTA structure lacks in workspace, it makes up in the stiffness and force (or impendace) bandwidth. It is difficult to obtain a normalized comparison between the forces produced by the two mechanisms. On the specifications, PHANToM declared 6.4N as maximum exertible force for the model above, as compared to 25N continuous force in the entire workspace for DELTA.

4.3. Inertia and Backdrivability

Both PHANToM and DELTA have light link structures. However, parallel mechanisms (such as DELTA) have multiple 'arms' and hence more inertia associated with the links. They also tend to be larger to produce enough workspace.

PHANToM uses cable drive which resulted in a very minimum friction and inertia (<75g for PHANToM 6 DOF model.) However, the design for joints 2 and 3 are such that the actuators for these joints move with the links. There is a mechanical counter-weight for joint 2. This reduces the apparent inertia in joint 2 and 3, but adds to that of joint 1.

DELTA has all its motor for the 3 DOF of translational motion permanently fixed at the base (see Figure 2) leaving only the links as moving parts. However, it uses a timing belt for transmission due to its large structure. Timing belt also introduces additional unwanted dynamics reflected at the end-effector, because it always has to be set at a certain amount of tension.

The use of cable drive and timing belt instead of gears ensures that these mechanisms are backdrivable and do not have backlash problems. As mentioned earlier, both designs introduce wrist attachment to provide the rotational degrees of freedom. These wrist modules also add to the apparent inertia of the mechanisms.

On the topic of isotropy, it should be noted that effort should be limited according to the sensitivity of human kinaesthetic perception, especially when the inertia is already reduced to be very light. Generally, it is hard to distinguish the difference in reflected inertia in different direction in both PHANToM and DELTA.

V. SUMMARY

As the main objective of a haptic interface is to provide a high fidelity force display to the user, design efforts should be focused towards a backdrivable and light weight mechanism. Being a general purpose haptic device, it is also desired to have a reasonable workspace, although workspace is often designed for specific applications. Various strategies were presented and discussed. It is necessary in the design to take into account the sensitivity of human perception. This would be the lower limit of the design criteria. The design effort is inseparable from the control challenges. A good force control algorithm requires a good dynamic model of the mechanism. For some haptic devices, friction effect has to be compensated properly to achieve better control performance. Since filtered velocity has undesired delay problem, a velocity observer could be used instead. Other problem in haptic application is the noisy measurements of the interaction forces between an environment and the slave or tele-operated robot: how to remove the noise without degrading the system performance is another issue that needs to be investigated.

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