The HapticMaster, a new high-performance haptic interface

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Abstract

The article addresses the technical principles of a new high-performance haptic device, called HapticMaster, and gives an overview of its haptic performance. The HapticMaster utilizes the admittance control paradigm, which facilitates high stiffness, large forces, and a high force sensitivity. On top of that the HapticMaster has a large workspace, and a huge haptic resolution. Typical applications for the HapticMaster are therefore found in virtual reality, haptics research, and rehabilitation.

1. Introduction

More than a dozen haptic interfaces are commercially available today. Lately, a new high-performance haptic device has been developed by FCS Control Systems (Fig. 1). It is called the HapticMaster, and it is now commercially available. In Japan it is called the ForceMaster out of respect for Prof. Iwata, who built a device with a similar name earlier.

Fig. 1 The HapticMaster, a new haptic device built by FCS Control Systems and now commercially available.

Haptic devices come in two distinct classes: impedance controlled devices, and admittance controlled devices. The HapticMaster belongs to the latter class. Both classes will be briefly discussed.

Impedance control was first introduced by Hogan (1985). The essential control paradigm is this: the user moves the haptic device, and the device will react with a force if a virtual object is met. So, viewed from the haptic device, the paradigm is: displacement in, and force out. The user will inevitably feel the mass and friction of the actual device, but these can be made very small by careful mechanical design. Impedance controlled devices are by nature lightly built and highly backdrivable. They are typically cable driven by high-performance DC motors. A prime example of the impedance control paradigm is Sensable's well-known series of Phantom devices.

Admittance control is the inverse of impedance control, hence the name. In admittance control the paradigm is this: the user exerts a force on the haptic device, and the device will react with the proper displacement. So, viewed from the haptic device, the paradigm is: force in, and displacement out. Admittance control allows considerable freedom in the mechanical design of the device, because backlash and tip inertia can be eliminated. As a result, the mechanism can be quite robust, capable of displaying high stiffnesses and high forces. Admittance control has been used for control sticks in the flight simulator industry for many years. A recent example of a generic haptics device using the admittance control paradigm is the FCS HapticMaster.

Impedance control and admittance control are dual not only in their cause-and-effect structure, but also in their performance. The impedance control device is typically lightweight, backlash free, and renders low mass [Adams & Hannaford, 2001]. Consequently, performance is lacking in the region of higher forces, high mass and high stiffness. Adding complex end effectors is also a problem. Admittance control devices on the other hand are capable of rendering very high stiffnesses and minimal friction, giving a very free feel to the motion. They are very suitable for larger workspaces, and also for master-slave applications and for carrying complex end effectors with many degrees of freedom. Also, they intrinsically register forces encountered, and are therefore very suitable for haptics and neurological research. However, they are often not capable of rendering very low mass.

The differences between impedance and admittance controlled haptic devices have an effect on their typical areas application. These will therefore be discussed at the end of this article, preceded by the principles of operation and the haptic performance of the HapticMaster.

2. Principles of operation

The principles of operation of the HapticMaster are discussed in three sections. First the control algorithm is presented, next the hardware and the software involved are discussed.

2.1 The control algorithm

The HapticMaster measures the force exerted by the user, preferably measured close to the human hand with a sensitive force sensor. An internal model then calculates the Position, Velocity, and Acceleration (PVA), which a (virtual) object touched in space would get as a result of this force. The PVA-vector is commanded to the robot, which then makes the movement by means of a conventional control law. The general control algorithm is illustrated in Fig. 2. The internal model will typically contain a certain mass, to avoid commanding infinite accelerations. The inner servo loop will cancel the real mass and friction of the mechanical device.

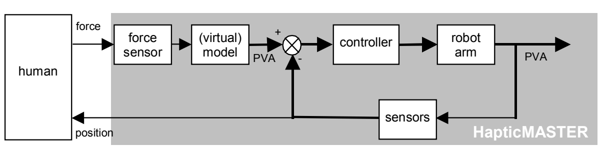

Fig. 2 *The general control scheme of the HapticMaster comprises an outer control loop, and an in inner servo loop. A (virtual) model converts the force sensor signal to a Position/Velocity/Acceleration setpoint vector. The inner servo loop controls the robot to the PVA setpoint values.*

2.2 The hardware

The hardware comprises two main functional components (Fig. 1): the robot arm, and the control box. Logically the first serves as the actual force display, whereas the second houses the amplifiers, and the haptic server.

2.2.1 The robot arm

The mechanism of the robot arm is built for zero backlash, which yields some friction in the joints. However, the friction is completely eliminated by the control loop, up to the accuracy of the force sensor. The result is a near backlash-free and smooth moving behavior at the end effector.

The workspace of the HapticMaster is depicted in Fig. 3. The kinematic chain from the bottom up yields: base rotation, arm up/down, arm in/out, illustrated in Fig. 4. This makes 3 degrees of freedom at the end effector, which spans a volumetric workspace. The HapticMaster is designed for exchangeable end effectors, to match an appropriate end effector to the end application. For instance an end effector with 3 additional rotations can be mounted at the end plate of the robot arm.

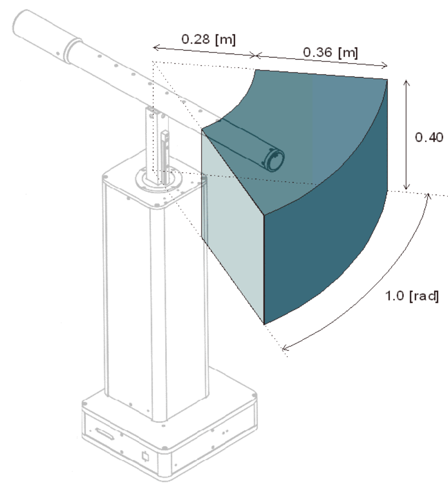

Fig. 3 *The end effector plate workspace of the HapticMaster spans a 3-dimensional space with a volume of approximately 80 liters. The end plate of the robot arm allows the mounting of different end effectors.*

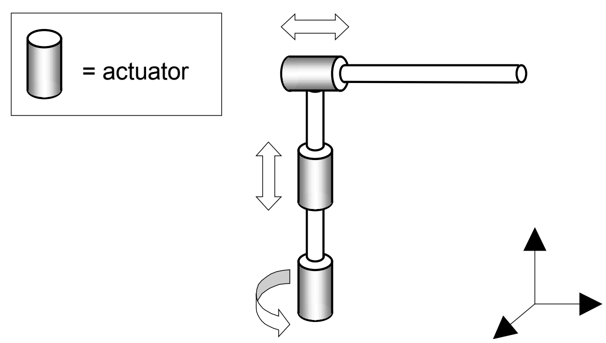

Fig. 4 *The actuator arrangement and the kinematics of the HapticMaster*

2.2.2 The haptic server

The haptic renderer and the robot control loop both run on a dedicated industrial PC with the VxWorks© real-time operating system. These two loops run at a fixed update rate of 2500 Hz. Because this frequency is approximately ten times higher than the maximal human discrepancy value [Burdea, 1996], it is assumed to be high enough to guarantee a haptic quality for a smooth and realistic experience. Using the principle of a haptic server also unloads the host PC.

2.3 The software

The software comprises a programming interface, to create haptic worlds, and a real-time operating system, to render the haptic world. The real-time application incorporates issues like safety guards, communication protocols, the control loop, collision detection of virtual objects, etc. Only the collision detection algorithm will be briefly discussed.

2.3.1 The programming interface

The HapticMaster is programmed by means of a HapticAPI, which is a C^{++} programming interface that enables the user to control the HapticMaster and create virtual haptic worlds. The HapticAPI is used to make an Ethernet connection to the HapticMaster to control the internal state machine and to define or modify the virtual haptic world. Haptic effects can be created, like dampers and springs, and spatial geometrical primitives can be defined, like spheres, cones and cubes. Also, the measured force, position, and velocity can be read. An example of a virtual haptic world, created by means of the FCS HapticAPI, and visualized by means of OpenGL is given in Fig. 5.

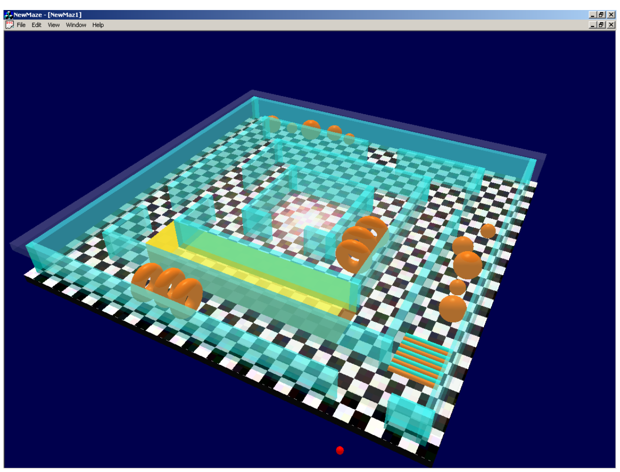

Fig. 5 *An example of a virtual haptic world, created with the HapticAPI and visualized with OpenGL. Geometrical primitives like spheres and cubes, and force elements like springs and dampers can be placed into a virtual world.*

2.3.2 The collision detection algorithm

When the end effector collides with a virtual object, an appropriate force and displacement must be presented to the user. The relationship between these two is given by the object properties (e.g. stiffness, damping, friction, etc.). With a penalty-based method the appropriate relation between force and displacement is calculated by the real-time operating system.

3. Haptic performance

A plethora of performance indicators can be given for haptic interfaces [Hayward and Astley, 1996]. For quantification of the haptic performance of the HapticMaster the following indicators were chosen: workspace, position resolution, stiffness, nominal/ maximal force, minimal tip inertia, maximum velocity, maximum deceleration, force sensitivity, frequency response, haptic resolution, force depth, and inertial ratio. The first eight indicators will be given in a simple specs table, whereas the latter four will be separately discussed. All indicators are given with respect to the end effector.

3.1 Specs table

The haptic specifications of the HapticMaster are given in Table 1.

Table 1, *specs of the HapticMaster*

Workspace	$80 \cdot 10^{-3}$ [m^3]
Position resolution†	$4 \cdot 10^{-6}$-$12 \cdot 10^{-6}$ [m]
Stiffness†	$10 \cdot 10^{3}$-$50 \cdot 10^{3}$ [N/m]
Nominal/max force	100/250 [N]
Minimal tip inertia	2 [kg]
Maximum velocity	1.0 [m/s]
Maximum deceleration	50 [m/s^2]
Force sensitivity	0.01 [N]

†depending on the degree of freedom and the position

3.2 Frequency response

The transfer function $H_N(\omega)$ of a haptic device at the end effector can be quantified by dividing the commanded acceleration (a_C) with the measured acceleration (a_M)

$$H_N(\omega) = \frac{a_M(\omega)}{a_C(\omega)}$$

Where N is the degree of freedom measured.
If we assume the force sensor to be infinitely fast, then the force at the end effector is proportional to the end effector acceleration. Fig. 6 gives the magnitude plot of the defined transfer function for the up/down movement for frequencies up to 25 Hz. It can be seen that the frequency response is fairly straight till 10 Hz, with a slight amplitude incline from 10 to 25 Hz.

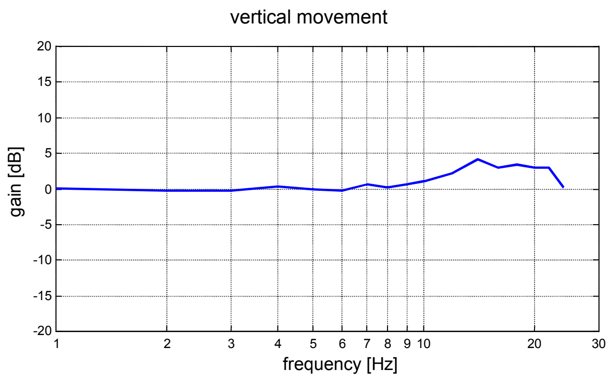

Fig. 6 *The frequency response of the vertical movement of the HapticMaster. The gain is obtained by division of the measured end effector acceleration and the commanded acceleration.*

3.3 Haptic resolution

Most large-workspace haptic devices have less position accuracy at the end effector than small-workspace devices. This is a logical consequence, because for articulated devices rotational measurements of the joints must be more accurate to obtain the same position accuracy at the tip. To correct for this size influence, the workspace is divided by the third power of the position resolution, which yields the haptic resolution (*HR*):

$$HR = \frac{workspace}{position\ resolution^3}$$

The haptic resolution gives an approximation of the number of volumetric units (voxels) that the device can render in space. For the HapticMaster the haptic resolution thus equals $1.25 \cdot 10^{15}$ [voxels], which is the largest haptic resolution of all commercially available haptic devices today. For comparison, this is approximately 3000 times higher than the haptic resolution of a Phantom desktop.

3.4 Force depth

Most powerful haptic devices have less force accuracy at the end effector than weak devices. This seems to be logical, because for impedance controlled devices more power implies more mass and more joint friction. Since impedance controlled haptic devices without force feedback are not able to render forces below the back drive friction, this is the smallest increment for force rendering. By dividing the nominal force by the back drive friction, the number of force increments is obtained, which we will call the force depth (*FD*):

$$FD = \frac{nominal\ force}{position\ resolution^3}$$

For the HapticMaster the force depth yields 10.000 increments. This is approximately 200 times higher than most impedance controlled devices.

3.5 Inertial ratio

There is a physical relationship between the tip inertia and robot mass. Simply comparing the tip inertia of a big and strong device with the tip inertia of a small and weak device, gives an incomplete picture of haptic performance. To correct for this, the minimal tip inertia is divided by the maximum stiffness of a haptic device, which yields the inertial ratio (*IR*):

$$IR = \frac{\min tip\ inertia}{\max stiffness}$$

The inertial ratio is a measure for the haptic dynamic range, because it gives the ratio between freely moving objects and constrained objects. For the HapticMaster the inertial ratio yields $0.04 \cdot 10^{-3}$ [s^{-2}]. For comparison, this is similar to a Phantom Premium 1.0.

4. Typical applications

In the previous section performance parameters were given for the HapticMaster. By comparing the HapticMaster to other commercially available haptic devices, it can be concluded that the HapticMaster excels on: force, force depth, stiffness, position resolution, and haptic resolution. Based on these characteristics the HapticMaster highly qualifies for the following typical applications.

- **Virtual reality**

Virtual reality applications especially benefit from the HapticMaster's performance when stiff or heavy objects must be rendered. Also, the rendering of curved stiff objects (e.g. car skins) requires a high haptic resolution. The HapticMaster therefore typically qualifies for virtual design and assembly tasks.

- **Haptics research**

Haptics research is performed in many different areas, from finger movement to arm movement in a combination with auditory, visual, kinesthetic or tactile sensing. Because the HapticMaster measures real force with the force sensor in the end effector, additional man-machine interaction measurements can be accurately performed.

- **Rehabilitation**

Rehabilitation and neurological research requires the force of the HapticMaster because the human limbs (e.g. the arm) must be carried and moved around [Harwin, 1999]. Given the workspace, and ability to measure force, the HapticMaster is highly suitable to perform this function.

5. Conclusions

A new high-performance haptic device, called the HapticMaster, is discussed in this article. The HapticMaster excels on the haptic performance indicators force, force depth, stiffness, position resolution, and haptic resolution. These key advantages facilitate typical applications like virtual assembly, haptics research and rehabilitation.

6. Future developments

In the near future different end effectors will be developed, facilitating different applications. A gimbal end effector will soon be commercially available. It will have three measured passive degrees of freedom, and one degree of freedom for an active gripping function. Also, the HapticAPI will be functionally extended to support software interfaces of third parties and incorporate issues like triangularization, dynamic environments, etc.

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