The Rutgers Master II—New Design Force-Feedback Glove

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***Abstract*—The Rutgers Master II-ND glove is a haptic interface designed for dextrous interactions with virtual environments. The glove provides force feedback up to 16 N each to the thumb, index, middle, and ring fingertips. It uses custom pneumatic actuators arranged in a direct-drive configuration in the palm. Unlike commercial haptic gloves, the direct-drive actuators make unnecessary cables and pulleys, resulting in a more compact and lighter structure. The force-feedback structure also serves as position measuring exoskeleton, by integrating noncontact Hall-effect and infrared sensors. The glove is connected to a haptic-control interface that reads its sensors and servos its actuators. The interface has pneumatic servovalves, signal conditioning electronics, A/D/A boards, power supply and an imbedded Pentium PC. This distributed computing assures much faster control bandwidth than would otherwise be possible. Communication with the host PC is done over an RS232 line. Comparative data with the CyberGrasp commercial haptic glove is presented.**

***Index Terms*—Calibration, control, CyberGlove, CyberGrasp, haptic feedback, position sensor, Rutgers Master glove, virtual reality.**

I. Introduction

VIRTUAL reality can be defined as the user's real-time multimodal interaction with a computer generated world [3]. This interaction is mediated by several sensorial channels, namely by the visual and auditory ones, and more recently by the haptic channel. The special computer hardware needed to capture user input and provide multimodal computer feedback is called an interface device.

Haptic feedback for virtual reality simulations groups the touch- and force-feedback modalities [4]. Touch feedback is needed to replicate virtual object surface mechanical smoothness, slippage, temperature, and contact geometry. Force feedback opposes the user's motion, and is intended to convey information on virtual object hardness, weight, and inertia. Haptic feedback (either tactile, force, or in combination) increases the simulation realism and the application domain of virtual environments. For example, it is hard to imagine how a surgical simulator could be useful without haptics. Furthermore, force and touch feedback become mandatory in poor visibility, or for the manipulation of visually–occluded objects.

The most used haptic interface today is a small backdrivable robotic arm called the "PHANToM" [11]. This desktop system measures the position and orientation of the user's index fingertip and provides small resistive forces at high control bandwidth (1000 Hz). This interface has high dynamic range and superb force fidelity. However, it lacks dexterity (only one finger has force feedback) and it limits the user's freedom of motion due to its small work envelope.

A complex category of haptic interfaces is force-feedback gloves, used for dextrous manipulation of virtual objects. Such simulations are those for CAD/CAM design [8], multiplexed telerobotics [9], hand rehabilitation [14], etc. Force-feedback gloves need to provide sustained forces to multiple fingers, should be light (to minimize user fatigue), need to be safe, and should preserve the user's natural arm freedom of motion as much as possible.

This article describes the Rutgers Master II "New Design" (RMII-ND) glove shown in Fig. 1(a). This haptic interface represents a follow-up to the RM and RM II gloves developed earlier in the Human-Machine Interface Laboratory at Rutgers University [2], [7]. Section II details the dual position sensing/force-feedback structure of the Rutgers Master II-ND glove and its calibration. Section III describes the glove electronic interface used for control and communication with the host computer, including its low-level force-feedback servocontrol. Experimentally obtained characteristics of the RMII-ND are given in Section IV. Section V compares them with those of the CyberGrasp, the only commercial haptic glove available at the time of this writing. Conclusions and future research directions are given in Section VI.

II. RMII-ND Glove Position Sensing/Force Feedback Structure

The interface position sensing exoskeleton consists of an "L"-shaped multilayer platform and four jointed actuators, as seen in Fig. 1(b). The shape of the platform is designed to fit comfortably behind the "middle-line" of the palm, and to allow the complete flexion of the metacarpal phalanx. This is

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(a)

(b)

Fig. 1. The Rutgers Master II—New design haptic interface. (a) General appearance of the prototype. (b) Position sensing and force-feedback structure. © Rutgers University CAIP Center. Reprinted by permission.

the finger segment that connects to the palm and has a "zero" position corresponding to a flat hand. The inside layer of the platform contains a small electronic printed board and four highly flexible pneumatic tubes that provide air to the feedback actuators. The bending of these PVC pneumatic tubes with the user's finger motion causes negligible resistive forces of 15–20 mN at the fingertips.

The structure linking each fingertip to the palm platform has three sensing joints and five degrees of freedom (DOF). Each actuator is attached to the base through a spherical joint (2-DOF). Its cylinder shaft can both translate in and out and rotate about the cylinder axis (2-DOF). Finally, the fingertip attachment connects to the cylinder shaft through a cylindrical joint (1-DOF).

The rotation axle of each rotary joint is mounted on two miniature bearings in order to reduce friction. Each glove incorporates a total of 24 miniature bearings. The actuator flexion motion (relative to the palm) varies from -10 to 120°, equivalent to the natural flexion of a proximal finger joint. This joint connects the palm to its fingers. The actuator abduction/adduction motion (in the plane of the palm) varies from $\pm 60°$, a range of motion that is larger than the corresponding natural motion of a finger. The piston stroke varies from 28–44 mm, depending on finger size. The second finger joint is called proximal-inter-phalangeal (PIP) while the distal joint is the one furthest from the palm. The piston linear motion range allows a maximum flexion angle of 45° for the PIP and distal finger joints. This represents typically 55% of the natural grasping motion and is due to the placing of the exoskeleton in the palm.

A. Actuator Structure

All RMII-ND actuators use two Hall-effect sensors to measure the flexion and adduction/abduction angles, as shown in Fig. 2(a). An infrared sensor, shown in Fig. 2(b), measures the translation of the piston inside an air cylinder. Both types of sensors are noncontact and thus they do not introduce friction forces in the process of measuring the actuator position. This choice of sensors minimizes friction which otherwise can have an unwanted "filtering effect" on small computer-generated feedback forces.

Each Hall-effect sensor uses two small magnetic discs made of rare earth material with a high flux density. This material has poles oriented to provide a stable and uniform magnetic field around the spherical joint. The sensor magnetic sensitivity (3 mV/Gauss) and the A/D conversion resolution (1.25 mV/5 V), give a theoretical angular resolution of 0.075°.

The RMII-ND custom designed pneumatic actuators have a high stroke/cylinder-length ratio, low friction, a large force/weight ratio, and compact construction. The actuator stroke/cylinder-length ratio varies depending on the finger range of motion. The compact design of the actuator results in a ratio of 45% for cylinder lengths of 40–60 mm. This compares favorably with conventional air cylinder actuators that have ratios of 25–35%.

The friction coefficient is an important parameter for any haptic device, since it affects the sensitivity and dynamic range of the interface. This in turn affects the quality of the interaction with a virtual environment. The RMII-ND actuator low friction results from the use of a graphite piston running smoothly inside a Pyrex glass cylinder [shown in Fig. 2(b)]. Both the inside of the cylinder and that of the piston have a fine-polished surface and tight tolerances. The piston is fixed to an axle trough a 3-DOF spherical joint. This mounting eliminates the constraint caused by misalignments between the cylinder and the axle and reduces the friction of the axle with the cylinder head seal. The glass cylinder is encased in a thin aluminum tube with a small space left in-between. The aluminum tube supports the entire lateral forces and provides excellent shock protection. The weight of an RMII-ND actuator, including its sensor, joints, and finger attachment, is 10 g. The actuator construction can resist a lateral loading of 20 N and axial loading exceeding 50 N.

An infrared reflective sensor measures the piston translation in and out of the cylinder. A small infrared emitter and two receivers are mounted in the bottom seal of the air cylinder facing a thin mirror mounted on the piston. Compared to the earlier

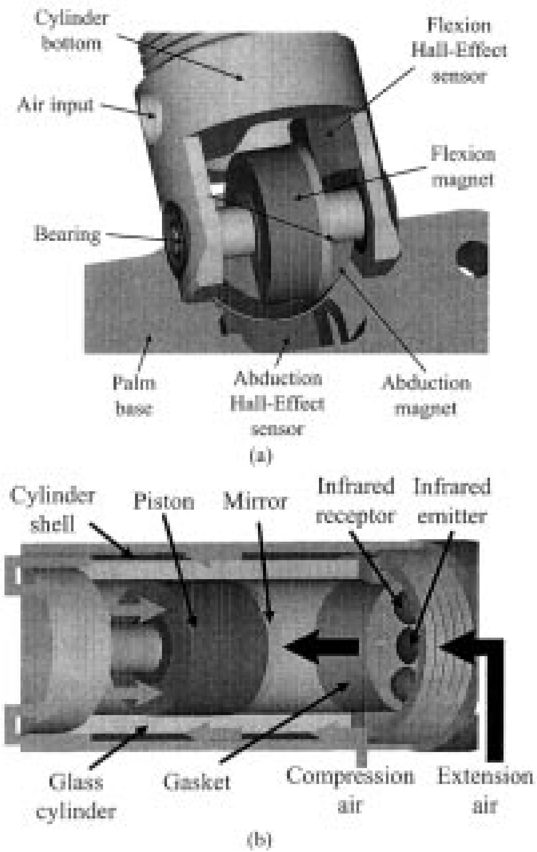


Fig. 2. Open view of the RMII-ND actuator construction. (a) Sensorized spherical joint. (b) Section through the cylinder. © Rutgers University CAIP Center. Reprinted by permission.

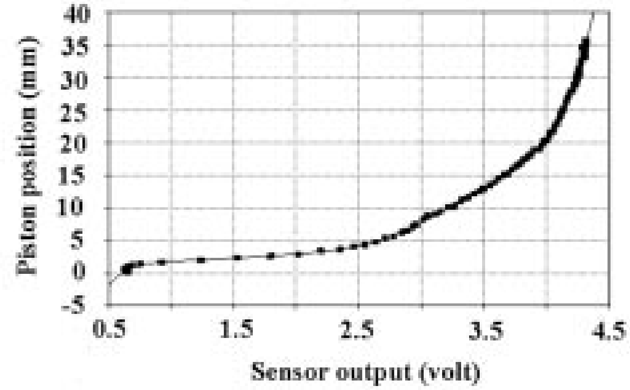


Fig. 3. Calibration curve for the piston IR position sensor. © Rutgers University CAIP Center. Reprinted by permission.

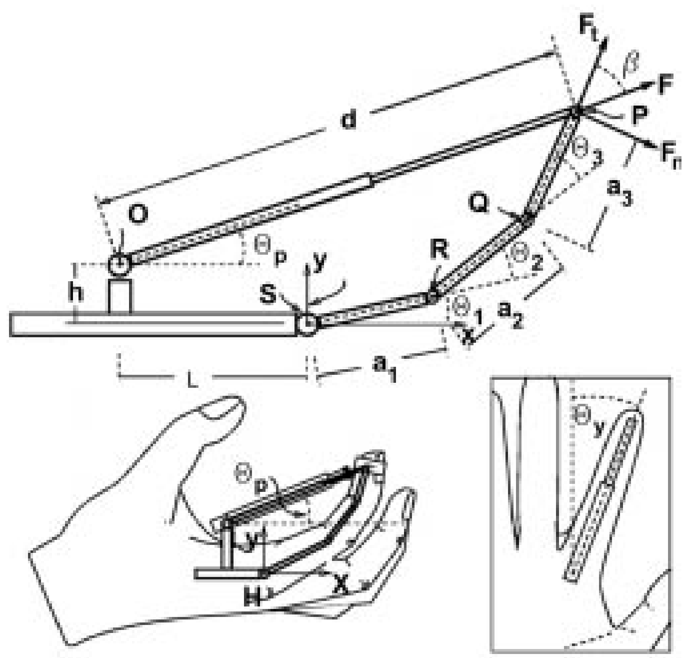


Fig. 4. RMII glove modeling: Position variables and finger kinematics model [6], [7]. © 1995 IEEE. Reprinted by permission.

RMII prototype, where the emitter was mounted on the piston, the RMII-ND solution is more compact. Its design eliminates the need for (unwanted) wires at the glove fingertip. One of the IR receivers is oriented such that its output reaches its minimum voltage (or maximum intensity) when the piston is approximately at the middle of the cylinder. This signal characteristic is due to the small area of the reflective mirror (5.6 mm diameter) compared to the piston displacement (44 mm). An additional infrared receiver is oriented with a larger inclination angle than the first receiver. The second IR receiver output is maximum when the piston is close to the bottom and is very small when the piston reaches the middle of the cylinder. An analog combination of the two receiver outputs produces a linear function that can be interpolated by a fifth-order polynomial, as illustrated in Fig. 3. The piston displacement is then determined using a function interpolating each part of the sensor output curve.

B. Virtual Hand Modeling

The virtual reality simulation is rendered on a host computer. It uses the interface sensor data in order to display a 3-D graphical hand to which the user's real hand is "mapped." The parameters used to determine a particular hand gesture are illustrated in Fig. 4. The finger abduction-adduction angle θ_y, together with the piston displacement D, and the piston angle θ_p, are used to determine the finger joint angles θ_1, θ_2, θ_3. The kinematic system does not depend on the abduction-adduction angle θ_y.

This is due to the fact that the flexion angle is measured along the axis of the finger, hence it is not affected by the abduction-adduction motion. Another parameter that does not appear in the kinematic model is the rotation angle of the finger around the axis of the piston. Since the position of the fingertip is considered to be a point, this rotation angle does not affect our model. The equations for the corresponding inverse kinematics problem are

$$a_1{}^*S_1 + a_2{}^*S_{1+2} + a_3{}^*S_{1+2+3} = D^*Sp + h \qquad (1)$$
$$a_1{}^*C_1 + a_2{}^*C_{1+2} + a_3{}^*C_{1+2+3} = D^*Cp - l. \qquad (2)$$

Additionally, a constraint equation exists for the angles θ_3 and θ_2 due to the coupling of these joints [10]

$$\theta_3 = 0.46^*\theta_2 + 0.083^*\theta_2^2. \qquad (3)$$

Since the system of equations (1)–(3) is nonlinear, a close form solution is difficult to find. Instead, a lookup table is used to solve the inverse kinematics problem. The lookup table consists of a two-dimensional array indexed by the values of D and θ_p and containing in each cell the corresponding θ_1 and θ_2 values. The angle θ_3 is calculated using (3).

The lookup table for finger joint angles is generated in two steps. First a 10 000 (D, θ_p) element preliminary table is obtained by giving values to θ_1 and θ_2 between 0° and 99° in 1° increments. Then the preliminary table is reversed with D and θ_p ordered from the smallest to the largest and cells filled with the corresponding (θ_1, θ_2) values. The values of D and θ_p need to be truncated before reversing the preliminary table, which causes some (D, θ_p) pairs to collapse. Hence, there are multiple (θ_1, θ_2) pairs corresponding to a single (D, θ_p) pair, reducing the accuracy of the computed θ_1 and θ_2. To invert the table, the unique value for one pair (D, θ_p) is taken as the mean of all corresponding pairs (θ_1, θ_2). The inversion uses a linear search for ordering (D, θ_p) and is computationally intensive. Furthermore, the position of the base of the pistons is changing with respect to the palm when the fingers are moving. This causes errors in measurement, which further reduce the precision of the solution θ_1, θ_2, and θ_3.

A simpler method with good results in practice is to approximate the surfaces $D = f(\theta_1, \theta_2)$ and $\theta_p = f(\theta_1, \theta_2)$ from the preliminary table as planar surfaces. The linear approximation equations are

$$D = a_1{}^*\theta_1 + b_1{}^*\theta_2 + c_1 \tag{4}$$
$$\theta_p = a_2{}^*\theta_1 + b_2{}^*\theta_2 + c_2. \tag{5}$$

A least-square method is used to calculate the plane's equation for θ_p. This method gives large errors at the extremities of the θ_1 and θ_2 domains. For D, we are interested in fitting the values that correspond to the extreme finger positions (totally bent, or fully open). These plane-fitting points correspond to several finger configurations. One configuration has the fingers opened $(\theta_1 = 0,\ \theta_2 = 0)$. Another has the metacarpal-proximal (MP) joint bent toward the palm and the PIP joint extended $(\theta_1 = 95,\ \theta_2 = 0)$. Yet another finger configuration for which plane-fitting points are calculated has the MP joint extended and the PIP joint bent toward the palm $(\theta_1 = 0,\ \theta_2 = 95)$. Accuracy needs to be good at these configurations, because graphics feedback makes errors obvious to the user in these cases. θ_1 and θ_2 are, therefore, calculated at run time as linear functions of sensor readings D and θ_p

$$\theta_1 = \frac{a_2{}^*D - b_1{}^*\theta_p + b_1{}^*c_2 - b_2{}^*c_1}{a_1{}^*b_2 - b_1{}^*a_2} \tag{6}$$
$$\theta_2 = \frac{(a_1{}^*\theta_p - a_2{}^*D - a_1{}^*c_2 + a_2{}^*c_1}{a_1{}^*b_2 - b_1{}^*a_2}. \tag{7}$$

The fingertip position error for this approximate method is under 13 mm, with a maximum around the middle of the 0° to 95°θ_p domain.

III. Haptic Control Interface

The haptic glove is controlled by an electronic interface called the "haptic-control interface." This arrangement distributes the computational load and allows faster control than would be possible with the host computer doing both graphics and physical modeling computations. The following sections describe the electromechanical components of the control interface, and the servocontrol it implements.

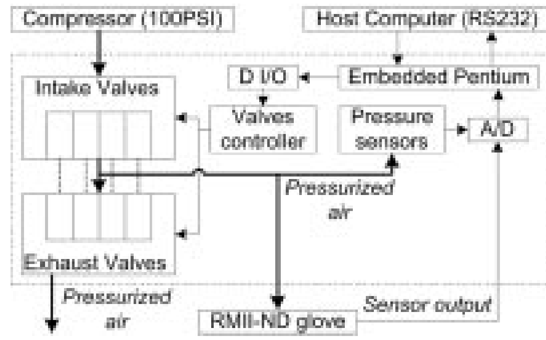


Fig. 5. The haptic-control interface functional diagram. Adapted from [14]. © 2000 IEEE. Reprinted by permission.

A. Circuitry

The haptic-control interface is illustrated in Fig. 5 [14]. It consists of an embedded Pentium PC, pneumatic valves and electronic boards for reading the glove sensors and implementing pressure control. The embedded PC is a 233 MHz Pentium board with PC104 bus, Disk-on-Chip memory, IDE, VGA and Ethernet interfaces. It is used as a controller (during glove normal operation), and as a platform for developing, testing and debugging the control software. An A/D/A board (MPC550 from Micro/Sys) with 16 input/8 output channels is mounted on the PC104 bus. Twelve of its A/D inputs read the glove position sensors, while the remaining four A/D inputs read the pressure sensors used in the control loop. Half of the output D/A channels control the intake microvalves inside the control interface pneumatic valves, while the other half control the corresponding exhaust valves.

Custom electronic boards in the interface box perform filtering, and amplification of the glove analog signals. Signals from IR and Hall effect sensors are then sampled by the A/D board. Analog pressure sensor signals are first amplified then converted to digital values. Analog outputs of the D/A board are amplified as well, prior to being applied to the pneumatic valves own control boards.

B. Low-Level Servocontrol and Communication With the Host

The Pentium PC embedded in the haptic-control interface performs three tasks: sensor reading, force-feedback control, and communication with the host computer (see Fig. 6). Data from the glove sensors are read in a continuous loop, at a frequency of about 1000 updates per second. The sensor signals are filtered to eliminate the electronic noise and sub-sampled to reduce the update frequency to the frequency of communication with the host computer.

The embedded computer controls the solenoid valves using a pulsewidth modulation (PWM) technique running at a frequency of 300 Hz. The pulse duration is calculated using a) the cylinder pressure measured by the sensor installed on the valves output pipes and the desired pressure determined by the host computer; b) the flow model for the inlet and outlet solenoids, which is a function of the main input pressure, and the room tem-

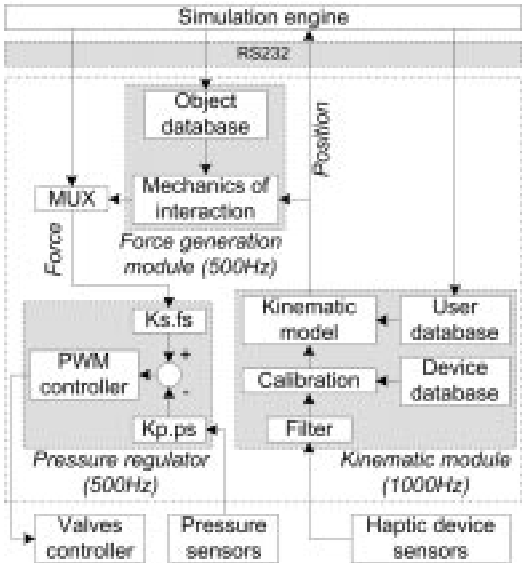


Fig. 6. Servoloop block diagram. © Rutgers University CAIP Center. Reprinted by permission.

perature; and c) the flow model of the cylinder and the tubing. The maximum flow rate of the solenoid valves is 200 Nl/min, with an opening (or closing) response time of about 2 ms.

The embedded PC communicates with the host computer using an RS232 serial line with baud-rates between 38 400–115 200 b/s. The data sent to the host computer include joint angles (or the raw sensor measurements such as displacement, flexion angle and abduction angle), measured forces and device state. The host computer sends commands for retrieving data, applying forces or for changing the functioning mode. When haptic rendering runs on the host computer, target forces are also continuously sent to the embedded PC.

The communication driver on the host computer is a standalone thread that reads and writes to the PC serial port. The software thread takes little processor time and memory due to the timeouts caused by the serial port I/O operations and the small size of the data packets. The communication is based on a request–answer protocol. The host computer is continuously requesting data from the serial port. The continuous loop is interrupted to serve other data communication requests, such as sending start and stop force commands for the "local force rendering" mode (described later in this section), changing the functioning mode, or for calibration. The haptic interface waits for a request from the host computer, serves the request and then goes back into a waiting state. In order to avoid overloading the interface, the request loop on the host computer limits its frequency according to the serial port baud-rate.

The communication flow is asymmetric, with much more data going to the host computer than to the control interface. In the continuous loop mode the size of a data packet sent from the host computer to the interface varies between one and six bytes, while a packet sent from the control interface to the host computer has fourteen to twenty bytes. Further details on host-interface communication performance are reported in Section IV.

C. Force-Feedback Modeling

When the virtual hand interacts with virtual objects, the corresponding *real* forces need to be applied to the user's hand. Interaction forces can be calculated in two ways: a) *local force rendering mode*—forces are computed locally by the haptic-control interface based on its parametric model, and b) *external force rendering mode*—forces are computed by the host PC and sent to the control interface to be displayed by the glove. The general force model is

$$F = k^* x + b^* \dot{x} + u \tag{8}$$

where x is a displacement proportional to the penetration distance of the virtual fingertips into a virtual object. The model parameters are: stiffness k, viscosity b, and offset force u. This offset force can be used to model friction as well as to implement some haptic effects such as constant force, step force, etc.

In local force rendering mode the forces are computed and displayed by the haptic-control interface, based on parameters received from the host computer. The host computer only commands the beginning and the end of the force-feedback loop, based on its collision detection task performed during the simulation. This method limits the number and complexity of models that can be stored in the object database. Local force rendering is, therefore, only suited for grasp-release type of interactions, as it assumes that the relative position of the hand and grasped object does not change.

In external force rendering mode, forces are calculated by the host and transmitted to the haptic-control interface as servoloop targets. The host computer uses collision detection and physical modeling laws to calculate the interaction forces between virtual fingers and virtual objects[13]. The limitation of the second method relates to the bandwidth of the communication between the host computer and the control interface. A dual-processor PC is the preferred configuration in this case, in order to allow faster computation of force targets, and faster overall system response.

IV. EXPERIMENTAL EVALUATION OF THE RUTGERS MASTER GLOVE

The weight of the RMII-ND glove exoskeleton structure is approximately 80 g. This small weight makes the RM glove very comfortable to wear, without undue user fatigue. The weight of the electric wires and pneumatic tubing connecting the master glove to its electronic controller is 105 g. This cable has a length of 2 m, providing a large work envelope for the user's arm, whether the user is sitting or standing.

An experimental setup consisting of a software controlled pressure regulator, an RMII-ND actuator and a load cell was used to test the system mechanical bandwidth [12]. The load cell was mounted at one end of an RMII piston to record the force as felt at the fingertip. Air was controlled by the Matrix valves, which received step function and sinusoidal driving signals. The valve noise was also recorded.

The Matrix-based software-controlled pressure regulator had a good response time to a 10 Hz step sign, as shown in Fig. 7. The model of the Matrix valve used in these experiments had eight internal microvalves. One, two, four, and eight Matrix microvalves per finger were subsequently tested to select the best pressure regulator configuration. The performance gain saturated after two microvalves per finger, while the noise level increased with more than 7 dB. A soundproof enclosure was subsequently built around the pneumatic valves reducing the noise

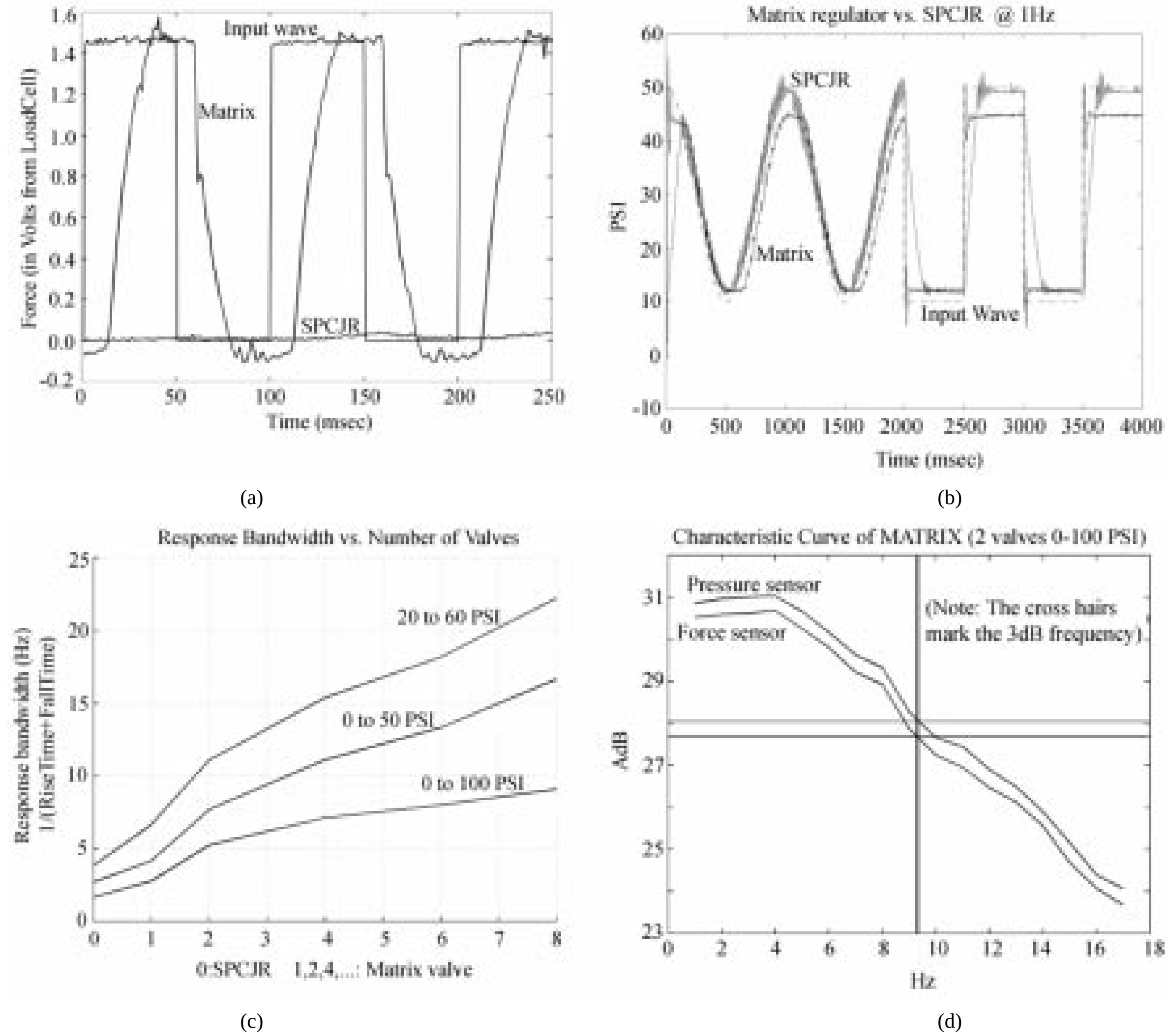
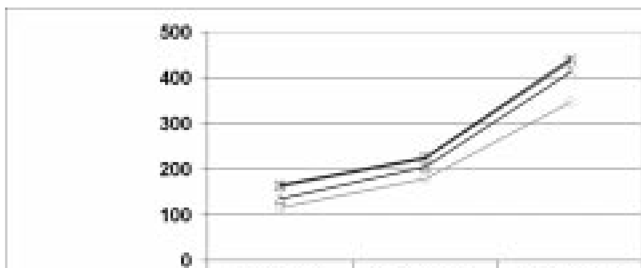


Fig. 7. Solenoid valves performance. (a) Matrix at 10 Hz. (b) Matrix at 1 Hz. (c) Response bandwidth versus air flow. (d) Characteristic curve of matrix regulator with two valves [12]. © Rutger University CAIP Center. Reprinted by permission.

by 6 dB. Additionally, by using two microvalves per finger, only two valves (a 1-to-8 intake and an 8-to-1 exhaust) were enough to implement the pressure regulator for four fingers.

The average linear sensor resolution, or the minimum piston displacement detected by the sensor, was experimentally evaluated at 0.25 mm. The accuracy of the measured piston position was less than 0.5 mm. The actual angular resolution was experimentally measured at 0.45°, essentially due to ambient electronic noise. The output of the Hall-effect position sensor was subsequently calibrated using an optical encoder. The curve plotting the angle versus the output voltage represented a third-order polynomial. After calibration, the angular accuracy was measured at 0.75° for the abduction/adduction angle and 1.25° for the flexion angle. This accuracy error was less than 1.5% of the total range of motion, due mostly to the calibration setup.

The number of data packets sent and received per second by the haptic-control interface varied depending on the serial port settings, on the type of data sent and on whether forces were being sent or not. Fig. 8 illustrates the performance obtained for different baud-rates on a Pentium III dual 933 MHz processor. The test application was a WorldToolKit (Sense8 Co.) simulation containing a virtual hand driven by the RMII-ND glove. The application was run five times for two minutse each and the average of the communication rates was computed. When forces were not controlled from the PC host, at a rate of 38 400 b/s the driver sent 165 RM-II position/force data sets every second



	Baudrate 38400	Baudrate 57600	Baudrate 115200
Raw data	165	226	440
Angles	162	222	435
Raw data+Forces	135	204	411
Angles+Forces	116	179	346

Fig. 8. RMII-ND serial line communication performance. © Rutgers University CAIP Center. Reprinted by permission.

Fig. 9. The CyberGrasp haptic glove. Photo courtesy of Immersion Co. Reprinted by permission.

to the PC host. At 115 200 b/s this rate went up to 440 data sets/second. This compares favorably to the data rate of the commercial CyberGlove (149 updates/s at 115 200 b/s), while being smaller than that of a Phantom device ($\sim$1000 updates/s) interfaced with a PCI card. When forces are controlled from the host PC, the communication rate dropped by 6% to 30% depending on the serial port baud rate setting. When the forces are controlled remotely the communication load from the PC host to the interface increases. Since the experimental data showed that the PC host and the control interface could handle high communication rates it is obvious that the bottleneck in this system is the serial port.

V. Comparison of the Rutgers Master Glove With the CyberGlove

At the time of this writing the only commercial force-feedback glove the authors are aware of is the CyberGrasp [15], illustrated in Fig. 9.

This interface uses electrical actuators placed remotely from the hand and low-friction tendons routed through an exoskeleton to transmit forces to the fingertips. It has a joint position resolution of 0.5° and a peak force of 12 N/fingertip. Its major drawback is its large weight (350 g), which can produce fatigue due to the lever effect of the arm. No data exists on its dynamic range, which should be negatively impacted by the known backlash effect of cables and tendons. This friction and hystheresis are the reason for the relatively low CyberGrasp mechanical bandwidth of 40 Hz. The CyberGrasp is more complex than the RMII-ND since a separate CyberGlove sensing glove is needed to measure finger position. Its advantage over the RMII-ND is that is provides force feedback to all fingers, and it preserves the hand work envelope. This is due to the placement of the exoskeleton on the back of the hand. The exoskeleton placement on the back of the hand results in the preservation of a palm-free area, which allows manipulation of real objects while wearing the interface. However, it does raise safety concerns, since fingers are pulled backwards, and could potentially hurt the user in case of a malfunction. The CyberGrasp addresses this issue through mechanical adjustment of the cable length to account for varying user hand sizes. It is then left up to the user to properly adjust the cable lengths. The RMII-ND glove differs from the CyberGrasp due to its use of direct-drive actuators placed in the palm. This exoskeleton structure has about the third of the weight of the CyberGrasp. The placement of the actuators in the palm prevents however the complete closing of the hand during grasps, and hinders manipulation of real objects while wearing the interface. The RMII-ND mechanically stops the fingers from being pushed backwards. This fail-safe design does not need adjustments on the part of the user. Table I [1] summarizes the characteristics of the RMII-ND glove as compared to those of the CybegGrasp/CyberGlove combination.

TABLE I
COMPARISON BETWEEN THE CHARACTERISTICS OF THE RMII VERSUS THE CYBERGRASP/CYBERGLOVE [1]. (© RUTGERS UNIVERSITY CAIP CENTER. REPRINTED BY PERMISSION)

Variable	RMII-ND Haptic Glove	CyberGlove with CyberGrasp
	Sensing	
Sensor placement	Built into actuators	Separate sensing glove
Sensor type	Non-contact (IR and Hall effect)	Resistive bend sensors
Sensor linearity	0.6% over full range	0.6% over full joint range
Sensor resolution	0.1 degree (Hall sensor); 0.3 mm IR sensor	0.5 degree
Sensor update rate	435 records/sec	112 records/sec
Communication Interface	RS232 (115 kbaud max)	RS232 (115 kbaud max)
	Force Feedback	
Maximum continuous force	16 N per finger (no force at pinkie)	12 N per finger (all fingers)
Minimum force	0.014 N (static actuator friction)	No data available
Force resolution	12 bit	12 bit
Actuator type	Pneumatic (direct drive)	DC motor, cables and cam
Bandwidth	300 Hz for valve control, 10 Hz at fingertip	1000 Hz for control, 40 Hz at fingertip
Work-space	2 meter radius hemisphere	1 meter radius hemisphere
Weight	Less than 100 g	539 g
Finger range	Limited	Full hand closing
Safety	Actuator range	Adjustable mechanical stops
Size	One size fits most	One size fits most
Sensor update rate (angles and forces)	346 records/sec	No data available
Communication Interface	RS232 (115 kbaud max)	RS232 (115 kbaud max)

VI. Conclusion and Future Work

The Rutgers Master II-ND glove is a haptic interface designed for dextrous interactions with virtual environments. The glove provides force feedback up to 16 N each to the thumb, index, middle, and ring fingertips. It uses custom pneumatic actuators arranged in a direct-drive configuration in the palm. Unlike the CyberGrasp commercial haptic glove, the RMII-ND direct-drive actuators make unnecessary cables and pulleys, resulting in a much more compact and lighter structure. The force-feedback structure has a dual role as position measuring exoskeleton, by integrating noncontact Hall-effect and infrared sensors. There is no need, therefore, for a separate sensing glove. The glove is connected to a haptic-control interface that reads its sensors and servos its actuators. The interface has pneumatic servovalves, signal conditioning electronics, A/D/A boards, power supply and an imbedded Pentium PC. This distributed computing arrangement offloads the physical modeling task from the host computer, and assures much faster control bandwidth than would otherwise be possible. Communication with the host PC is done over an RS232 line, assuring transmission of 346 complete hand position data and force targets every second.

To date the Rutgers Master II-ND has been successfully integrated with several types of virtual reality applications, ranging from hand rehabilitation to military command and control. The glove has been constructed to allow use with small or large hand sizes, by allowing flexibility in the placement of the exoskeleton in the palm. A dual-glove (left and right) system is currently under construction. This system will use a single control interface that has sufficient computing power to handle both gloves simultaneously. The haptic-control interface is currently being redesigned to allow operation of the Rutgers Ankle haptic platform [5]. This will allow the choice of haptics for the upper or lower portion of the body, or a combination thereof.

References

[1] M. Bouzit, G. Popescu, G. Burdea, and R. Boian, "The Rutgers Master II-ND force feedback glove," in *Proc. 10th Haptic Interfaces for Virtual Environments and Teleoperator Systems*, Orlando, FL, Mar. 2002, pp. 145–152.

[2] G. Burdea, N. Langrana, E. Roskos, D. Silver, and J. Zhuang, "A portable dextrous master with force feedback," in *Presence*. Cambridge, MA: MIT Press, 1992, vol. 1, pp. 18–28.

[3] G. Burdea and P. Coiffet, *Virtual Reality Technology*. New York: Wiley, 1994.

[4] G. Burdea, *Force and Touch Feedback for Virtual Reality*. New York: Wiley, 1996.

[5] M. Girone, G. Burdea, M. Bouzit, V. Popescu, and J. Deutsch, "A Stewart platform-based system for ankle telerehabilitation," *Autonom. Robots*, vol. 10, pp. 203–212, Mar. 2001.

[6] D. Gomez, G. Burdea, and N. Langrana, "Integration of the Rutgers Master II in a virtual reality simulation," in *Proc. VRAIS*, 1995, pp. 198–202.

[7] D. Gomez, "A dextrous hand master with force feedback for virtual reality," Ph.D. dissertation, Rutgers Univ., New Brunswick, NJ, 1997.

[8] S. Jayaram, Y. Wang, U. Jayaram, K. Lyons, and P. Hart, "A virtual assembly design environment," in *Proc. VR*, Mar. 1999, pp. 172–179.

[9] A. Kheddar, C. Tzafestas, P. Coiffet, T. Kotoku, S. Kawabata, K. Iwamoto, K. Tanie, I. Mazon, C. Laugier, and R. Chellali, "Parallel multi-robot long distance teleoperation," in *Proc. ICAR*, Monterey, CA, 1997, pp. 1007–1012.

[10] J. W. Lee and K. Rim, "Maximum finger force prediction using a planar simulation of the middle finger," in *Proc. Instrumentation Mechanical Engineering*, vol. 204, 1990, pp. 160–178.

[11] T. Massie and J. Salisbury, "The PHANToM haptic interface: A device for probing virtual objects," in *Proc. ASME Winter Annu. Meeting Symp. Haptic Interfaces for Virtual Environment and Teleoperator Systems*, vol. DSC-55-1, 1994, pp. 295–300.

[12] G. Patounakis, M. Bouzit, and G. Burdea, "Study of the electromechanical bandwidth of the Rutgers Master," Rutgers Univ., New Brunswick, NJ, CAIP-TR-225, 1998.

[13] V. Popescu, G. Burdea, and M. Bouzit, "Virtual reality modeling for a haptic glove," in *Proc Computer Animation*, Geneva, Switzerland, May 1999, pp. 195–200.

[14] V. Popescu, G. Burdea, M. Bouzit, M. Girone, and V. Hentz, "Orthopedic telerehabilitation with virtual force feedback," *IEEE Trans. Inform. Technol. Biomed.*, vol. 4, pp. 45–51, Mar. 2000.

[15] M. Turner, D. Gomez, M. Tremblay, and M. Cutkosky, "Preliminary tests of an arm-grounded haptic feedback device in telemanipulation," in *Proc. ASME WAM*, vol. DSC-64, 1998, pp. 145–149.

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