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The Rutgers Master II-ND Force Feedback Glove[1]

Mourad Bouzit, George Popescu, Grigore Burdea and Rares Boian
Center for Advanced Information Processing
Rutgers – The State University of New Jersey, Piscataway NJ 08854,
USA.
{bouzit, vpopescu, burdea, boian}@vr.rutgers.edu

Abstract

The Rutgers Master II-ND glove is a follow up on the earlier Rutgers Master II haptic interface. The redesigned glove has all the sensing placed on palm support, avoiding routing wires to the fingertips. It uses custom pneumatic actuators arranged in a direct-drive configuration between the palm and the thumb, index middle and ring fingers. The supporting glove used in the RMII design is eliminated, thus the RMII-ND can better accommodate varying hand sizes. The glove is connected to a haptic control interface that reads its sensors and servos its actuators. The interface pneumatic pulse-width modulated servo-valves have higher bandwidth than those used in the earlier RMII, resulting in better force control. A comparison with the CyberGrasp commercial haptic glove is provided.

1. Introduction

The most widespread type of haptic interface today is the “PHANToM” arm [7]. This desktop system provides small resistive forces to the user’s index at high bandwidth (1000 Hz). The PHANToM is unable to sustain high forces due to electrical actuator overheating and it lacks dexterity, since only one finger has force feedback. Finally, the interface limits the user's freedom of motion due to its small work envelope.

A complex category of haptic interfaces is force feedback gloves, used in dexterous manipulation of virtual objects. Force feedback gloves should provide sustained forces to multiple fingers, need to be light (to minimize user fatigue), be safe to use, and should preserve the user's natural arm freedom of motion as much as possible. The only commercial force feedback glove today is the CyberGrasp [5]. Since the position data necessary in the simulation is measured by a separate CyberGlove, the overall system is expensive. Research at Rutgers Human-Machine Interface Lab was aimed at unifying the sensing and force feedback in a single glove. This resulted in the Rutgers Master II prototype (Figure 1-a) developed in the mid nineties [4]. This glove design was problematic since it had sensors placed at the fingertip, and exposed pneumatic tubes and wiring. This paper describes the follow-up Rutgers Master II “New Design” (ND) glove, shown in Figure 1b. Section 2 details its dual position-sensing/force-feedback structure and its calibration. Section 3 describes its electronic interface used for control and communication with the host computer, and the low-level force feedback servo control. Section 4 presents experimentally obtained characteristics of the RMII glove. Section 5 compares them with those of the CyberGrasp/CyberGlove. Conclusions and future research directions are given in Section 6.

2. The RMII-ND glove position sensing/force feedback structure

The interface position sensing exoskeleton consists of an "L"-shaped multi-layer platform and four jointed actuators, similar to the structure used in the earlier RMII. The shape of the platform is designed to fit comfortably behind the "middle-line" of the palm, and allow the complete flexion of the metacarpal phalanx. This is the finger segment that connects to the palm. 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 small 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 (two DOF). Its cylinder shaft can

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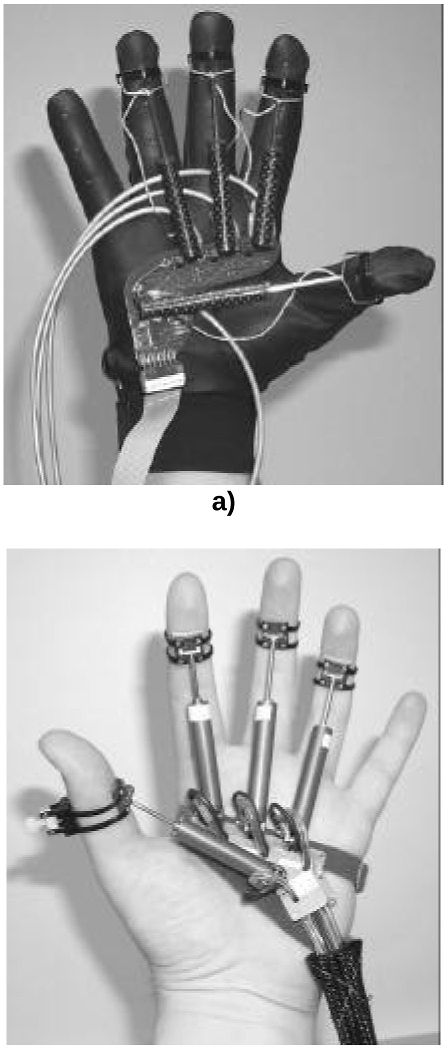
both translate and rotate (two DOF). The fingertip attachment connects to the cylinder shaft through a cylindrical joint (one DOF).

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^{o} to 120^{o}, 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 -60^{o} to $+60^{o}$, a range of motion that is larger than the corresponding natural motion of a finger.


a)

b)

Figure 1. The Rutgers Master II-New Design haptic interface: a) Rutgers Master II; b) Rutgers Master II-ND; © Rutgers University. Reprinted by permission.

The piston stroke varies from 28 mm to 44 mm, depending on finger size and the location of the finger attachment. 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^{o} 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 on the palm.

2.1. The actuator structure

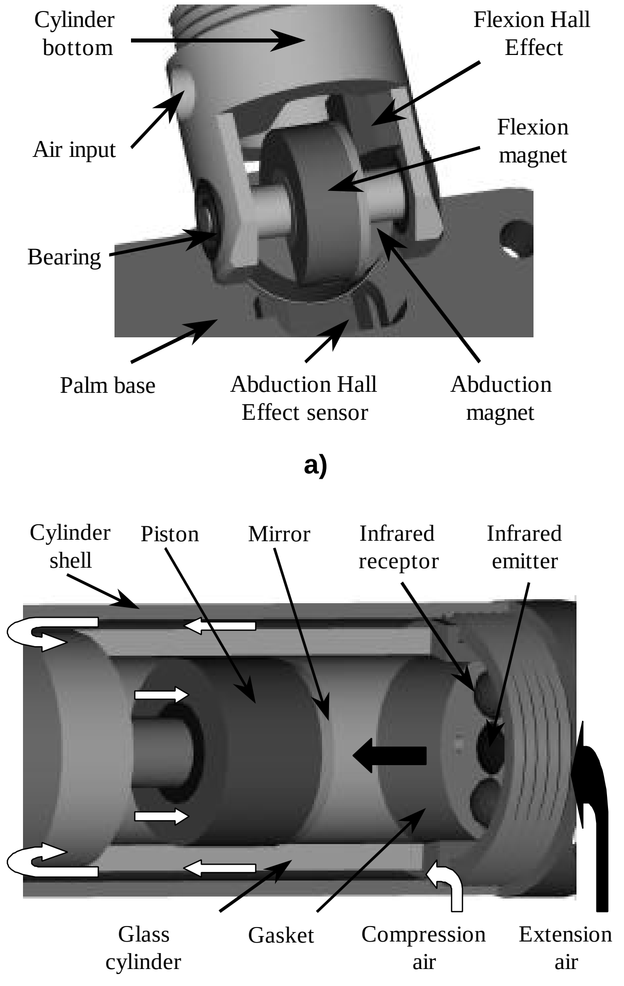
RMII-ND actuators use two Hall-effect sensors to measure the flexion and adduction/abduction angles, as shown in Figure 2-a. An infrared sensor, shown in Figure 2-b, measures the translation of the piston inside an air cylinder. Both types of sensors are non-contact and thus they do not introduce friction forces in the process of measuring position. The choice of sensors minimizes the “filtering effect” friction has on small computer-generated feedback forces.

Each Hall-effect sensor uses two small magnetic discs made of rare earth material with 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/5V), give a theoretical angular resolution of 0.075^{o}.

The RMII-ND custom-designed pneumatic actuators have a high stroke/cylinder-length ratio, ultra-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 RMII-ND 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 Figure 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 three-DOF spherical joint (Figure 2-a). 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 the actuator, including the sensor, joints, and finger attachment, is 10 g. The RMII-ND actuator construction can resist a lateral loading of 20 N and axial loading exceeding 50N.

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 RMII (earlier) prototype where the emitter was mounted on the piston, the RMII-ND solution is more compact and eliminates the need for unwanted wires at the glove fingertip. One of its two IR receivers is oriented such that its output reaches 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).



a)

b)

Figure 2. Open view of the RMII-ND actuator construction: a) sensorized spherical joint, b) section through the cylinder. © Rutgers University. Reprinted by permission.

An additional infrared receiver is oriented with a larger inclination angle than the first receiver. The second IR receiver output is largest when the piston is close to the bottom and 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 (Figure 3). The piston displacement is then determined using a function interpolating each part of the sensor output curve.

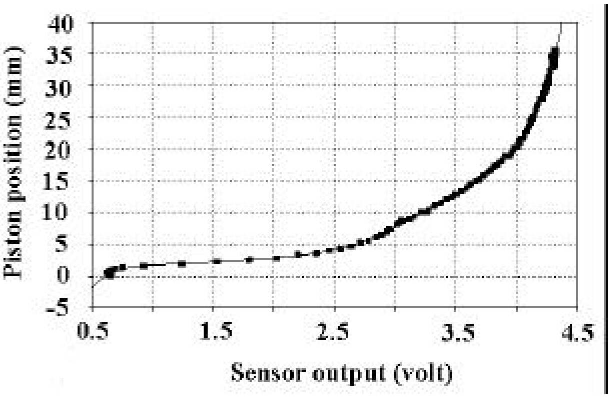


Figure 3. Calibration of the piston positions sensor with two infrared receivers. © Rutgers University. Reprinted by permission.

2.2. Virtual hand modeling

The RMII-ND hand master uses three sensor measurements to determine the position of the user's fingertips versus the palm. This information is needed by the host computer in order to render 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 Figure 4 [3]. The finger abduction-adduction angle θ_y, together with the piston displacement D, and the piston angle θ_p are used to determine finger joint angles θ_1, θ_2 and θ_3. The kinematic system does not depend on the abduction-adduction angle θ_y because the flexion angle is measured along the axis of the finger , hence the abduction-adduction motion does not affect it. 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 is not taken into account in our model. The equations for the corresponding inverse kinematics problem are:

$$a_1 * S_1 + a_2 * S_{1+2} + a_3 * S_{1+2+3} = D * Sp + h \tag{1}$$
$$a_1 * C_1 + a_2 * C_{1+2} + a_3 * C_{1+2+3} = D * Cp - l \tag{2}$$

Additionally, a constraint equation exists for the angles θ_3 and θ_2 due to the coupling of these joints [6]. Equation 3 has been derived for free motion of the fingers. When forces are applied to the fingertip, the distal joint tends to be extended. A coefficient proportional to the force can be applied to θ_3 to address this behavior.

$$\theta_3 = 0.46 * \theta_2 + 0.083 * \theta_2^2 \tag{3}$$

Since the system of equations (1–3) is nonlinear, a close form solution is difficult to find. Instead, a look-up table is used to solve the inverse kinematics problem. The look-up 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 equation (3).

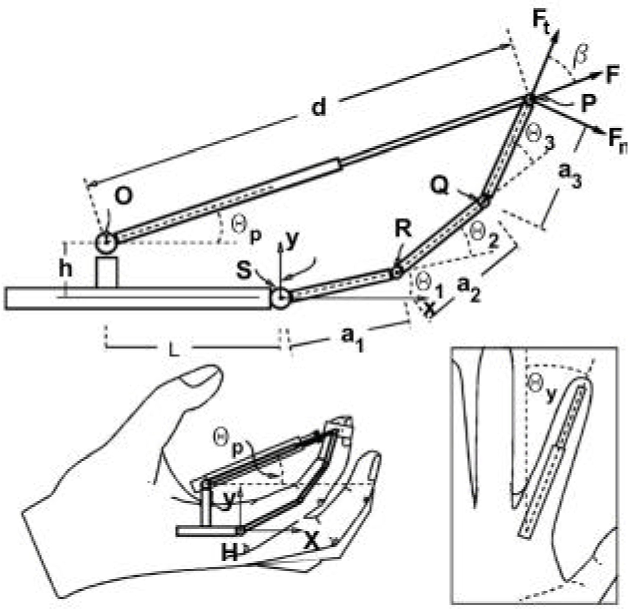


Figure 4. RMII-ND glove kinematics model [3]. © Rutgers University. Reprinted by permission.

The look-up 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 0º and 99º in 1º increments. Then the preliminary table is reversed with D and θ_p ordered from the smallest to 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, causing 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, we chose to take as the unique values for one pair (D, θ_p) the average mean of all corresponding pairs (θ_1, θ_2). The inversion uses a linear search for ordering (D, θ_p) and is computationally intensive. Additionally, the position of the base of the pistons is changing with respect to the palm when the fingers are moving. This induces errors in measurements, 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 (θ_1, θ_2) and θ_p = f (θ_1, θ_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 θ_1 and θ_2 domain. For D, we are interested in fitting the values that correspond to the limit position of the finger (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 towards the palm and the PIP joint extended ($\theta_1 = 95^{\circ}$, $\theta_2 = 0^{\circ}$). Yet another finger configuration for which plane-fitting points are calculated has the MP joint extended and the PIP joint bent towards the palm ($\theta_1 = 0$, $\theta_2 = 95$). Accuracy needs to be good at these configurations, because graphics feedback makes errors obvious in these particular cases. θ_1 and θ_2 are therefore calculated at run time as linear functions of sensor readings D and θ_p.

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

The fingertip position error for this approximation is under 13 mm, with a maximum around the middle of θ_p domain.

3. The 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 otherwise be possible with the host computer doing both graphics and physical modeling. The following sections describe the electromechanical components of the interface, and the servo control it implements.

3.1. Circuitry

The Haptic Control Interface is illustrated in Figure 5 [9]. 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 operation as well 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 micro-valves inside the pneumatic valves, while the other half control the exhaust ones.

Custom electronic boards in the interface box perform filtering, amplification and multiplexing of the analog signals. Signals from IR and Hall effect sensors mounted on the haptic glove are amplified and filtered before being 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 on the pneumatic valves own control boards.

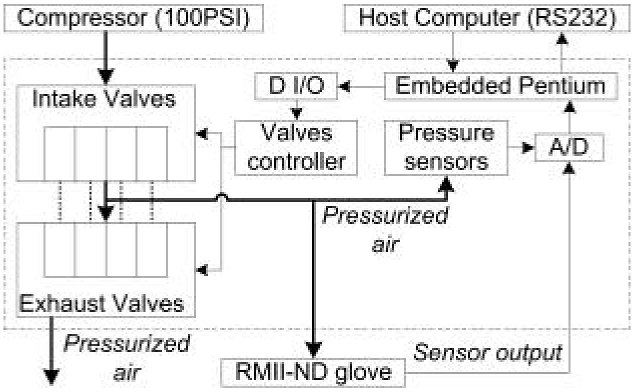


Figure 5. The Haptic Control Interface functional diagram. Adapted from [9] ã 2000 IEEE.

3.2. Low-level servo control and communication with the host

The embedded Pentium PC performs three tasks: sensor reading, force feedback control and communication with the host computer (Fig. 6). Data from the RMII-ND sensors are read in a continuous loop, filtered and then transformed into hand joint values. The frequency of sensor readings is about 1000 updates per second. The sensor readings 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 Pulse-Width Modulation (PWM) technique running at a frequency of 500 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 set by the host computer, b) the flow model for the inlet and outlet solenoid which is a function of the main input pressure, and the room temperature, c) the flow model of the actuator cylinder and the connecting tubing. The maximum flow rate of the solenoid valves is 200Nl/min and the opening (or closing) response time is 2ms.

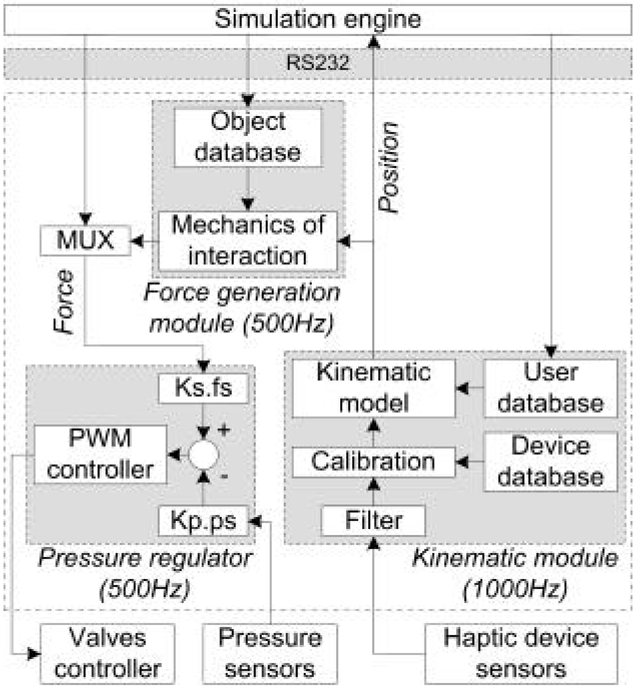


Figure 6. Servo loop block diagram. © Rutgers University. Reprinted by permission

The embedded PC communicates with the host computer using an RS232 serial port with baud-rates of 38,400–115,200BPS. The communication with the host computer uses an asynchronous protocol. The data sent by the control interface 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 control interface.

The communication driver on the host computer is a stand-alone thread that reads and writes to the 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, like sending start and stop force commands during "local force rendering" mode operation, changing the operating mode, or for calibration. The haptic interface waits for a request from the host computer, services it and then goes back to 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.

3.3. Force feedback modeling

When the virtual hand interacts with objects, the corresponding forces need to be applied to the user's hand. Interaction forces can be calculated using two different modes of operation: local force rendering – forces are calculated locally on the haptic interface based on a parametric model; and external force rendering – forces are calculated by the simulation engine are sent to the interface to be displayed. The local rendering use simple haptic effects to simulate the interaction while the external rendering models in finer detail the mechanics of the interaction. The general force model is:

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

where x is a displacement proportional to the penetration distance of the virtual fingertips. The model parameters are stiffness (k), viscosity (b) and offset force (u). The 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 operating mode the forces are calculated and displayed locally by the haptic control interface, based on parameters received from the host computer (as illustrated in Fig. 6). The host computer only commands the beginning and the end of the force feedback loop, based on its collision detection during the simulation. The limitation of this method resides in 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 as control targets to the haptic control interface. The host computer uses collision detection and physical modeling laws to calculate the interaction forces between virtual fingers and virtual objects [8]. The limitations of this method are related to the communication bandwidth 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.

4. Experimental Evaluation of the Rutgers Master Glove ND

The weight of the RMII-ND glove mechanical structure is approximately 80g. 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, whether the user is sitting or standing.

An experimental setup consisting of a software controlled pressure regulator, an RMII piston and a load cell was used to test the mechanical bandwidth obtained with the Matrix valves [8]. The performance was compared with a commercially available pressure regulator, SPCJR [1]. The load cell was mounted at one end of the RMII piston to record the force felt at the fingertip. The valve noise was also recorded.

The Matrix-based software-controlled pressure regulator had a good response time to a 10 Hz step signal. One, two, four and eight Matrix micro-valves per finger were subsequently tested to select the pressure regulator configuration. The performance gain saturated after two micro-valves per finger, while the noise level increased by more than 7dB. A soundproof enclosure was subsequently built around the pneumatic valves reducing the noise by 6dB. Therefore by choosing two micro-valves per finger the mechanical bandwidth of the haptic interface was three times that obtained with the SPCJR controller used in the earlier RMII version of the glove, while keeping the noise level in the same range. Additionally, by using two micro-valves 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.

Based on the piston diameter equal to 5.6mm and the cylinder air pressure equal to 6.55 bar or 95 psi (the maximum controlled pressure when the input pressure is 100 psi) the maximum force produced by actuator is

16.05N. The maximum force was also measured experimentally using a strain gauge force sensor. Since this is a pneumatic actuator, it does not overheat when applying constant forces for longer durations. The actuator friction was experimentally measured by first mounting the actuator in vertical position with atmospheric pressure inside it and than attaching a light mass to the piston shaft. The total weight of the load, piston and shaft that make the piston start moving down correspond the actuator friction. The RMII-ND friction measured an average of 14 mN (less than 0.1% of the piston maximum output). 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^o, 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 vs. the output voltage represented a third order polynomial. After calibration, the angular accuracy was measured at 0.75^o for the abduction/adduction angle and $1.25\,^o$ 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 sets sent and received per second depends on the serial port settings, on the type of data sent and on whether forces are being sent or not. The communication performance was obtained for different baud-rates on a dual processor Pentium III at 933 MHz. 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-minute periods each and the average of the communication rates was computed.

When forces were not controlled from the PC host, at a rate of 115,200 BPS the interface sent 440 position/force data sets/second. This compares favorably to the data rate of a CyberGlove (149 updates/sec at 115200 BPS), while being smaller than that of a Phantom device (1000 updates/sec). When forces were controlled from the host PC, the communication rate dropped to 346 data sets/sec. Since the data shows that the PC host and the interface could handle high communication rates it is obvious that the bottleneck in this system was the serial port.

5. Comparison of the RMII-ND glove with the CyberGrasp/CyberGlove

At the time of this writing the only commercial force feedback glove the authors are aware of is the CyberGrasp [5]. This interface uses electrical actuators placed remotely from the hand and low-friction tendons to transmit forces to the fingertips. It has a joint position resolution of 0.5^o and a peak force of 12 N/fingertip. Its major drawback is large weight (350 grams), which can produce fatigue due to the lever effect of the arm. Furthermore, no data exists on its dynamic range, which should be negatively impacted by the known backlash effect of cables and tendons. A third drawback is complexity, since a separate sensing glove (CyberGlove) is needed to measure finger position. Its advantages are force feedback to all fingers, preservation of handwork envelope, and the preservation of a palm-free area, which allows real object manipulation while wearing the interface.

The RMII-ND glove differs from the CyberGrasp due to its use of direct-drive actuators placed in the palm. This exoskeleton structure has less than a 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. Table 1 summarizes the characteristics of the RMII-ND glove as compared to those of the CyberGrasp/CyberGlove combination.

Table 1: Comparison between the characteristics of the RMII vs. those of the CyberGrasp/CyberGlove (based on [5]). © Rutgers University. Reprinted by permission

Variable	RMII-ND Haptic Glove	CyberGrasp Haptic Glove
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 deg (Hall-eff); 0.3mm (IR)	0.5 degree
Sensor update rate	435 records/sec	112 records/sec
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 Electric and cables
Bandwidth	500 Hz for control, 10 Hz at fingertip	No data available
Work-space	2 meter radius hemisphere	1 meter radius hemisphere
Exoskeleton weight	80 g	350 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)

6. Conclusions and Future Work

The Rutgers Master II-ND glove is a haptic interface designed for dexterous 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 much more compact and light structure. The force feedback structure has a dual role as position measuring exoskeleton, by integrating non-contact 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 servo-valves, signal conditioning electronics, A/D/A boards, power supply and an embedded Pentium PC. This distributed computing arrangement offloads the physical modeling task from the host computer, and assures much faster control bandwidth than would be otherwise possible. Communication with the host PC is done over an RS232 line, assuring over 300 complete hand position data and/or force targets to be transmitted 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 such that is accommodates varying hand sizes without a supportive glove. 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 same control interface is currently being designed to control our Rutgers Ankle haptic interface [2]. This will allow hand and foot haptic interaction with the VR simulation.

Acknowledgments

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Bibliography

[1] Buzmatics Inc., “SPCJR Unit Specifications,” Company brochure, Indianapolis IN, 4 pp.

[2] Girone M., Burdea, G., M. Bouzit, V.G. Popescu, and J. Deutsch, "A Stewart Platform-based System for Ankle Telerehabilitation," invited article, Special Issue on Personal Robotics, Autonomous Robots, Vol. 10, pp. 203-212, Kluwer, March 2001

[3] D. Gomez, G. Burdea, and N. Langrana, “Integration of the Rutgers Master II in a Virtual Reality Simulation,” *Proceedings VRAIS’95*, 1995, pp. 198–202.

[4] D. Gomez, “A Dextrous Hand Master with Force Feedback for Virtual Reality,” Ph.D. Thesis, Rutgers University, ECE Dept., 1997.

[5] Immersion Co., The CyberGrasp: Groundbreaking haptic interface for the entire hand, http://www.immersion.com/products/3d/interaction/cybergrasp.shtml, 2001.

[6] J.W. Lee, and K. Rim, “Maximum finger force prediction using a planar simulation of the middle finger,” *Proceedings of Instrumentation Mechanical Engineering*, Vol. 204, 1990, pp. 160–178.

[7] T. Massie, and J. Salisbury, “The PHANToM Haptic Interface: A Device For Probing Virtual Objects,” *Proceedings of the ASME Winter Annual Meeting Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, DSC-Vol. 55–1, New York, 1994, pp. 295–300,.

[8] G. Patounakis, M. Bouzit and G. Burdea, “Study of the Electromechanical Bandwidth of the Rutgers Master,” Technical Report CAIP-TR-225, Rutgers University, May 22, 1998.

[9] V. Popescu, G. Burdea, M. Bouzit. “Virtual Reality Modeling for a Haptic Glove,” *Proceedings of Computer Animation '99*, Geneva, May 1999, pp. 195-200.