A Virtual Reality-based System for Hand Diagnosis and Rehabilitation

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Key words: hand diagnosis, hand rehabilitation, virtual reality, force feedback, portable master.

Invited Article, *Presence – Teleoperation and Virtual Environments*, MIT Press, April 96.

Abstract

This article describes a new and unified approach to computerized hand diagnosis and rehabilitation. The system uses a workstation to automate diagnosis data collection and analysis and to assess the rehabilitation progress. A new diagnosis glove was developed and tested. This device measures grasping forces applied to 16 regions of the hand. A physician using this system can also utilize modern diagnosis devices such as electronic dynamometer, pinchmeter and goniometer. Additionaly, three VR rehabilitation exercises were created using WorldToolKit graphics library and run on the same workstation. These exercises were modeled after standard hand rehabilitation procedures and involve manipulation of virtual objects and transparent real-time data gathering. Grasping forces were modeled and fed back using the Rutgers Master worn on the patient's hand. An Oracle database was used to store, analyze and integrate the patient's diagnosis and rehabilitation data. The system is presently undergoing clinical trials.

1 Introduction

The human hand can be regarded as a biomechanical linkage system of intercalated bony segments. Between each phalanx, there are ligaments, tendons and muscles that span over the joints. With the constraint of the interposing soft tissue and bony articulations, the muscles can pull the joint and move it in a specific manner. The thumb and the four fingers have three joints each. The first joint of the thumb is the proximal joint or the carpometacarpal joint which has two degrees of freedom, i.e. adduction-abduction and flexion-extension, each with a range of around 90 degrees. The second joint of the thumb is the metacarpal-phalangeal joint, which has one degree of freedom of flexion-extension towards the palm. The third joint of the thumb is the distal joint or the interphalangeal joint which has one degree of freedom over a range of 90 degrees. The four fingers have three joints each – one metacarpal-phalangeal joint and two interphalangeal joints. The former has two degrees of freedom, 30 degrees adduction-abduction and 120 degrees flexion-extension. The latter are hinge joints which have one degree of freedom rotating approximately 90 degrees (Burdea & Jhuang, 1990).

Accurate and reliable evaluation of a patient's physical condition plays a very important role in the process of treating hand disabilities. The process of hand diagnosis involves measurements of grip strength, joint range of motion (ROM), and sensitivity to vibrations, light touch and temperature. Clinical evaluation of a patient's hand disability can be time-consuming since the physician is responsible for total impairment evaluation. Furthermore, the complexity of hand anatomy makes necessary multiple measurements in order to improve accuracy.

Conventional evaluation systems are based on manual measurements of each joint flexion and extension angles with the use of a goniometer. This process is tedious and sometimes inaccurate, since mechanical instruments are usually associated with position errors. During the course of treatment, it is desirable to repeat these measurements over time in order to assess the patient's progress. Due to the subjective element in the use of a goniometer the repeatability of any particular examination is relatively poor. It then becomes necessary that the same physician or hand therapist examine the same patient at each (subsequent) evaluation session. This may be inconvenient and sometimes impractical.

Mechanical manual instruments lack automated data transfer and are being replaced by electronic counterparts interfaced to a computer. This on-line data collecting capability can be a big asset for a physician, since it increases the number of measurements and allows faster patient diagnosis and report generation. Furthermore, computerized hand diagnostic systems such as "Eval" (Fox, 1991), "Clinical Hand Master" (Exos, 1990) and "Dexter" (Cederon Medical Systems, 1994) are more repeatable than traditional manual systems.

Eval is a computer-based examination system that links precision measurement tools with specially designed software to perform systematic, reproducible hand examinations. It's goal is to improve clinical efficiency and outperform manual exams in conducting test, collecting data, generating reports and analyzing information. Eval guides the therapist through the evaluation program, staring with medical, work-related, and other patient information. Subsequently, the patient goes through the various areas of evaluation, each on a different computer screen. The software is able to assess the full range of motion, the sensory and perception limitations, and the endurance and strength of upper extremities. It provides the user with information specifying the level of voluntary effort given by the patient, and therefore during the examination session a physician is able to determine whether a patient is giving maximum effort. Therefore a patient who has a tendency to be fearful of using his hand because of injury or just foul play can be detected. This feature of Eval is important for third-party carriers and worker's compensation. An examiner can acquire a total impairment measurement in a format of choice. The Eval form library includes third-party carrier standard forms and a comprehensive hand evaluation report form.

Eval can also evaluate edema in two different ways. In addition it offers three sensory tests and three grip tests. The computer has the capability of subjective input for pain evaluation, instability and the placement of arthroplasties. It allows to quantify the progress in grip and range of motion in evaluations done over the course of one year. The hardware used by Eval consists of electronic dynamometer, pinchmeter and goniometers for hand and upper extremity. These instruments are connected to a serial port interface system. They are used by the patient to perform manual tests according to the corresponding prompts appearing on the computer screen. Each examination displays a screen for recording data that are either entered automatically from the instrument, or manually by the examiner. The impairment rating produced by Eval is based on the American Medical Association guidelines (American Medical Association, 1988). All calculations of impairments and reports are performed automatically. Reports can be accessed and printed immediately, facilitating trend analysis and research.

The EXOS "Clinical Hand Master System" (CHMS) is an extension of EXOS sensing technology. This system measures joint motion (static and dynamic) using Hall-effect sensors developed for robotic application providing a physician with high level of speed, accuracy and repeatability. CHMS uses electronic dynamometer, pinchmeter and goniometers, similarly with Eval. Additionally, an exoskeleton structure is used for wrist evaluation. The battery of tests performed on the CHMS include range of motion (hand and upper extremity), grip strength, pinch strength, and video capture of the hand for cosmetics. The PC to which the instruments are interfaced then provides trend analysis of patient capabilities from visit to visit and comparative information pertaining to the patient.

The Dexter evaluation system produced by Cederon Medical is a spin-off of research done by NASA for hand evaluation in space. The Dexter system has several configurations such as Dexter Rehabilitation and Evaluation, the Table Top Evaluation System, or the Physician Desktop and Administrative Desktop. Depending on its configuration, the Dexter system can be used for AMA impairment rating, physical exams with the dynamometer and pinchmeter, or dynamic testing and rehabilitation.

The Dexter Center and Table Top testing models, which are the two most common, perform the data collection for range of motion, edema, manual muscle test, and anatomy. The software can sort and tabulate data with respect to categories such as sex, age, weight, pathology, treatment method, outcome and referring physician. Results can be compared over time for complete and thorough analysis. Dexter system also provides communication capabilities with the referring physician who can receive testing and therapy results via a modem and perform on-line impairment ratings, review patient records, update them and add progress notes. Utilization of portable and desktop computing with communications technology benefits therapist's contact with referring physicians, workman's compensation advisors, and companies interested in pre-placement screening or baseline testing.

Apart from the instruments used by the three systems described above, position sensing gloves have been proposed for hand diagnosis as well as rehabilitation. Wise et al. (1990) evaluated a DataGlove (VPL, 1987) for semi-automated goniometric measurements. The glove was used for a series of ROM tests with several subjects. MIP and PIP joint angles of the five digits were compared during repetitive motions to measure the repeatability of the glove. The results showed overall error of 5.6^o as compared with $5 - 8^o$ with manual measurements. Wise concluded that the sensing glove could be used for hand diagnosis as a semi-automated goniometric measurement device. The advantage, of course, is that a sensing glove can measure multiple joints simultaneously, while a goniometer can only measure a joint at a time. This can shorten the overall evaluation process, if inexpensive, reusable and reliable gloves become commercially-available. Unfortunately, the DataGlove used by Wise and his colleagues was both expensive and suffered from sensor coupling (Burdea & Coiffet, 1994). The motion of one joint influenced readings on another, even if the latter had not moved.

Force exertion data is obtained by the commercial systems described above with tools such as pinchmeters and dynamometers. These instruments do measure the forces either for the whole hand (dynamometer), or for several fingers (pinchmeter). The need for practical finger force sensors is well known in the field of hand biomechanics (An et al., 1985), clinical evaluation (Dickson, 1972) and rehabilitation (Crago, 1986). Most commercial force transducers are either too bulky, thus significantly degrading manual dexterity (An et al., 1985), or are too fragile (Pennywitt, 1986; Tan, 1988). A previous study performed in our laboratory looked at alternative force sensors comparing Force Sensitive Resistors (FSR), Miniature Strain Gauges and Ultrasonic Force Sensors (UFS) (Burdea et al., 1995-a) (Burdea, 1996). The results showed that UFS sensors were better suited for the purpose of measuring joint forces. They had large enough force range (14 kg) for our application and maintained a constant slope for the range of forces up to 4 kg. Based on these results, we have designed the Tactile Glove which uses UFS sensors mounted on a DataGlove. The prototype constructed under contract by Bonneville Scientific (Salt Lake City, UT) measured grasping forces at 16 different locations of the hand simultaneously. More details on the tactile glove construction can be found in (Burdea et al., 1995-b).

Rehabilitation is another important aspect of the process of treating a hand disability. Several exercising tools are available, some for individual fingers, such as the Digi-Key (North Coast Medical Inc., 1994), while others, such as rubber balls of different stiffnesses increase the grip strength of the whole hand. Other devices measure the ability to manipulate objects and test hand-eye coordination (eg: putting pegs in a board). Rehabilitation exercises are presently performed at specialized clinics and hospitals and require repeated visits by the patient.

Virtual rehabilitation exercises have recently been developed. While replicating exercises routinely done in the rehabilitation clinics, they make the rehabilitation process more pleasant for the patient and more challenging by utilizing a multi-sensorial, interactive, human-machine interface. Furthermore, the reduction in the price of PC-based 3-D graphics technology coupled with increased computational power will make possible future home-based rehabilitation.

Brown and her colleagues at Dartmouth College (1993) describe a prototype exoskeleton used as a prosthetic device by patients who have lost muscular control of their hand. The exoskeleton consists of a sensorized aluminum structure attached to the back of the hand wearing a Lycra glove. Hand position is measured by a PC host, which receives data from several rotary potentiometers integrated in the exoskeleton. Five cables routed to the palmar side of the hand are used to close the index and thumb in a pinching grasp.

Hogan and colleagues at MIT (1993) developed the "MIT–MANUS" workstation for manual therapy and training. The system consists of a five-degree-of-freedom robot manipulator and two PCs used for control and visual/auditory feedback to the patient. The robot has a custom brace which attaches to the patient's wrist, allowing both translation in a horizontal plane and rotation of the wrist (extension, abduction and pronation). Recent clinical trials at Burke Rehabilitation Hospital (White Plains, NY) (Krebs et al., 1996) used the above system for the neuro-rehabilitation of patients with a paralyzed upper limb following stroke. Initial results showed faster motor rehabilitation for patients using the MIT–MANUS system in addition to conventional therapy, compared to patients that had only conventional therapy.

Rehabilitation exercises using VR simulations are by no means limited to the hand. Takeda and Tsutsul (1993) at Nagasaki Institute of Applied Science have developed an orthosis for exercising of the patient's upper arm. The device is a structure which contains position sensors as well as force feedback actuators. The actuators are light pneumatic muscle like devices which contract when pressurized. The virtual environment consists of a room with virtual exercising equipment– springs, dumbell etc. which is seen by the patient through a head-mounted display. Unfortunately the dynamics associated with the pneumatics of the system remain a problem.

Durfee and Goldfarb (1993) at MIT have developed another orthosis based system. The system is intended for paraplegic patients who have lost their walking capabilities. The system integrated electrical stimulation with an energized lower limb support to reduce muscle fatigue (induced by electrical stimulation).

The rehabilitation component of the unified diagnostic/rehabilitation system presented in this paper takes a different approach by using the Rutgers Master I (RM I) force feedback interface (Burdea et al., 1992). The RM-I allows the "feel" of virtual objects using direct-drive actuators on the palm of a DataGlove that measures hand gestures. The feedback structure consists of four pneumatic micro–cylinders which are attached to the glove. The pinky does not have force feedback, thus cannot be exercised using the present setup.

In addition to performing hand diagnosis and assigning rehabilitation exercises to a patient, a physician has to keep accurate records of patient data. These records have to be complete, easy to read and update. We have designed a Motif style (OSF, 1991) graphical user interface (GUI) which uses an Oracle (Oracle Co., 1995) engine to manipulate data. The Oracle database is shared between the diagnostic and rehabilitation parts of the system, essentially unifying the two activities into a continuum. This Database allows the doctor to maintain an updated record on patient information as well as current medical status. It can plot various graphs corresponding to diagnosis data as well as progress in rehabilitation. Reports which follow current standards can be printed as well as electronically transferred for external consultation.

The unification of hand diagnosis and rehabilitation tools together with a supporting database in a single workstation makes the system unique. This integration may become a powerful medical tool for hand rehabilitation since it unifies all the important elements of hand therapy. Furthermore, the use of VR-based exercises for the individual fingers provides unmatched flexibility when compared with the other VR-based rehabilitation prototypes presented above.

Section 2 of this paper describes the overall system configuration while Section 3 details the various VR exercises used for hand rehabilitation. Section 4 presents the underlying integration software for data analysis and database maintenance. Section 5 discusses the present state of the system. Future research issues conclude this article.

2 System Configuration

The main component of our system is a Sun SPARCstation-10, as illustrated in Figure 1. It is running Solaris OS V2.0 configured with 64 MB of RAM to improve graphics performance. The workstation has a ZX graphics accelerator with a rendering speed of about 100,000 Gouraud-shaded polygons per second. The Sun workstation is also equipped with a data acquisition board (Analyx Systems Inc., 1993) having 16 analog inputs and four digital outputs. The board has 12 bit resolution and a conversion rate of 100 KHz. The diagnosis and rehabilitation subsystems interfaced to the workstation are described below.

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Place Figure 1 about here

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2.1 The Diagnosis Subsystem

The diagnosis subsystem consists of the Tactile Glove developed in our laboratory, as well as an electronic goniometer, an electronic pinchmeter and dynamometer (Cederon Medical). These are interfaced with the workstation via the A/D/A board. The dynamometer, pinchmeter and goniometer were calibrated and tests were performed to measure their accuracy and repeatability. It was found that the three instruments are almost 100% accurate and exhibit excellent repeatability. Nevertheless, the interface does give the user an option to recalibrate the instruments if needed.

The first eight A/D channels are connected to the Tactile Glove interface (described later) while channels 9 to 12 are used by the other disgnostic devices. The pinch meter and dynamometer output a single analog signal each, ranging from 0 to 5 V proportional to the forces applied by the patient, at a frequency of about 100 Hz. The goniometer outputs one analog signal (position sensor) and one digital signal (foot pedal). The pedal determines when the goniometer is read by the workstation. The digital signal is routed to an analog input (A12) since the A/D/A board lacks an extra digital input.

2.1.1 The Tactile Glove System

The Tactile Glove system consists of three components, a sensing glove, a tactile glove and an electronic interface box. The sensing glove is a DataGlove-like device shown in Figure 2. It uses 16 fiber optic sensors (flex sensors) mounted on the back of a lycra glove. Each sensor consists of an optical fiber that runs from the sensor interface to the finger joint and back. At one end of the fiber there is an IR LED emitter (source) while at the other end there is an IR photo transistor (sensor). The intensity of the transmitted light through the fiber is a function of the bending of the fiber at the finger joint. The more the joint bends, the less light is transmitted. In the flex sensor electronic interface there are 16 operational amplifiers that amplify and condition the signals from the flex sensors. The output of the flex sensor interface is then 16 analog signals (0 to 5V). Previous tests showed an overall average error of 5.6 degrees for this type of fiber optic gloves (Wise et al., 1990).

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Place Figure 2 about here

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The tactile glove is made of 16 ultrasonic force sensors (UFS) (BSI, 1995). The sensors are mounted directly on to the palmar side of the sensing glove. As shown in Figure 2, the placement of the UFS sensors was chosen such that they cover key locations on the palm and the fingers which experience force during grasping. The UFS sensors have two main components – the sensor body and the electronic driver circuit. The sensor body has three parts – the emitter-receiver plate, the sound-media element and the reflecting dish. The sensor measures force indirectly by measuring the size of the sound-media element. The electronic driver generates a sound pulse from the emitter-receiver plate, at the same time starting a timer device. The sound pulse travels through the sound-media and bounces back to the reflecting dish. At the instant the pulse returns to the emitter-receiver plate, the drivers stop the timer. The time of flight of the sound pulse is then a function of the size of the sound-media element. The larger the force applied to the sound-media element, the more it deforms and the less time is required for the sound pulse to travel back and forth. Time-of-flight to force conversion was implemented in software with an accuracy of 1%. Unfortunately, sensor noise problems have developed during testing and calibration.

Crosscoupling and large noise/signal ratios made calibration extremely difficult. This problem was compounded by the use of a single multiplexed timer for all 16 UFS sensors in the design developed by BSI. The short time of flight would have required a dedicated high speed timer for each sensor.

The main component of the Tactile Glove interface unit is a 32-to-8 analog multiplexer, as shown in Figure 3. Half of the inputs to the multiplexer are from the UFS sensors and the other half are from the sensing glove. The multiplexer is controlled by two digital lines providing four multiplexing states (00, 01, 10 and 11). Thus the interface has ten IO lines- eight analog outputs and two digital inputs. These signals are connected to the A/D/A board installed in the workstation and are read at a frequency of about 13 Hz. The software driver executes the mutiplexing sequence, at each stage reading eight analog inputs. At the end of this sequence an analog vector of 32 entries is formed, 16 for the UFS and 16 for the flex sensors.

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2.2 Other Diagnostic Tools

In addition to the Tactile Glove the diagnostic component of our system uses an electronic dynamometer, a pinch meter and a goniometer. These instruments record grip force, pinch force (key and tip) and range of motion respectively. The data obtained from the three instruments was saved and can be reviewed at a later time through our GUI. We also provide the user with the option to zoom into a force or ROM graph and examine a portion of the output more closely.

When using the dynamometer, the patient is asked to perform the grip test six times, alternating between the left and right hands. Therefore six sets of data are recorded. In this way, the physician can compare the patients "normal" hand grip force against the impaired hand. Six graphs are output as a result of this procedure.

The physician can choose between three kinds of pinch tests that a patient could perform. These are the three point pinch, lateral pinch and key pinch. The GUI guides a patient through a description of what he/she has to do for each pinch test. The physician can first demonstrate to the patient how the pinch test is performed. The pinch tests are done for both left and right hands and the maximum force for each pinch test is recorded.

The goniometer measures the bending angles for closing and opening of the fingers of both hands. The output of the procedure is a table with entries for the bending angles.

2.3 The Rehabilitation Subsystem

The rehabilitation subsystem uses the Rutgers Master (RM-I) retrofitted on a DataGlove. The DataGlove measures hand gestures and 3-D wrist positions at a rate of about 30 readings/sec and transmits this data to the Sun workstation over a serial line. The Rutgers Master is used for force feedback to the user's fingers. Its compact structure fits in the palm, as shown in Figure 1. The lightness of the feedback structure (about 100 grams) helps reduce user fatigue considerably. The feedback pressure is controlled by analog proportional regulators housed in an interface box. The maximum force experienced by each fingertip is about 4N (at an air pressure of about 100 psi). The force data is output by the workstation through its D/A channels as voltages which are then mapped to the air pressure.

3 VR Simulation

3.1 The 3-D Graphics

The main simulation code was written in C++. The graphics library used was WorldToolKit V2.1 (Sense8 Co., 1994). Support libraries with drivers for the A/D/A board, the Tactile Glove and RM-I were also written in C++. The main classes used are "

Tactile_Glove" and "RM_I" with a class hierarchy as illustrated in Figure 4. The Tactile Glove class interacts with the software driver for the UFS_Glove providing the application with current sensor data. RMI class maintains two interactions, with the Data_Glove for input and with the RM-I interface for output (force feedback) through the Analyx A/D/A board.

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Place Figure 4 about here

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Graphical simulations for both the diagnostic and rehabilitation subsystems were created. The simulation for hand diagnosis consists of a realistic model of the human right hand (obtained from ViewPoint Datalabs (1993)). This hand was divided into 16 segments, each mapping to a force sensor on the Tactile Glove. When a user wears the Tactile Glove and squeezes on a real object, each segment of the virtual hand changes color according to the force measured by the sensor to which the segment maps. This data is recorded and can be displayed by the graphing utility built into our GUI once the process of diagnosis is completed.

3.2 VR Exercises

WorldToolKit is a library of functions for the development of virtual environment simulations. It provides high level functions for creation of a virtual environment. WorldToolKit is structured in an object-oriented way, although it does not use inheritance or dynamic binding. A WorldToolKit program is associated with the notion of a universe which is like a container into which graphical objects are added. These objects can be attached to a sensor. A WorldToolKit application consists of a main loop in which various objects are loaded and various sensor devices are activated. This main loop is executed only once, but each of the sensors which are loaded are polled. The dynamics of an object are then determined by the sensor it is attached to. WorldToolKit provides functions to keep track of object interactions such collision detection by checking for intersection between bounding boxes of objects. The WTK loop in shown in Figure 5.

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Graphical objects are loaded from source files in "obj," "dxf" and "nff" formats. We used Autocad to create our 3-D objects in dxf format. These objects were then loaded into our VR environment. WorldToolKit supports several commercially-available input-output devices. However device drivers for the RM-I subsystem (which includes the Polhemus tracker and the DataGlove) and the Tactile Glove had to be added.

Since graphics refresh rate is an important simulation issue, and the large hand model from Viewpoint Datalabs was too complex (over 1500 polygons), it was reduced to a simpler model with less than 200 polygons. This increased the refresh rate from 5 fps to 16 fps. Refresh rates above 15 fps have been shown to be satisfactory for interactive graphics simulation (Richard et al., 1996). Experiments were also performed with different ways of implementing asynchronous communication via the serial port to see how a protocol affected latencies and the refresh rate of the VR simulation. We experimented with three different protocols for asynchronous communication. The first used low level functions to access the serial port. The second protocol was implemented using shared memory (the data from the serial port is written into a segment of shared memory from where it is then accessed by the WorldToolKit sensor update function). Lastly, a driver was implemented using standard WorldToolKit functions for reading the serial port and latencies were measured. Table 1 shows the change in frame rate depending on the protocol implemented and the hand model used.

On the rehabilitation side, which uses the RM I, three virtual exercises have been designed. All three are "virtual" versions of common exercises performed by hand rehabilitation patients. Before a user attempts to perform any of the exercises, the RM-I is calibrated for his/her hand size and range of motion. This is necessary in order to give the user a more accurate feedback within the virtual world. To do this, the user is asked to open and close his/her fist repeatedly. The minimum and maximum angles of flexion and extension are then recorded. By mapping the minimum angle to a "full closed" position of the graphical hand and the maximum angle to the "full open" position of the graphical hand, the virtual hand is made to map to the user's hand.

The first exercise involves squeezing of a virtual ball. Gravity is simulated so that the user sees a ball bouncing in a virtual room. The user can then follow and grab the ball and squeeze it repeatedly. Ball deformation is simulated by vertex level manipulation of the ball object. The stiffness of the ball can be adjusted according to the level of exercise difficulty. The computer keeps track of the number of squeezes performed by a patient. The application exits automatically once the desired number of squeezes (specified by the physician) has been performed, or generates an error message if the user performs fewer than the required number of squeezes. In this way, we provide a way to assure that a patient does not overdo his/her rehabilitation routine, and also keep the doctor informed if a routine is not completed. The forces experienced by each finger during the routine are recorded and can be visualized through the graphing facility in our GUI. We also record the average force/finger and the square root of sum of squared forces as a measure of total grasping effort.

The second rehabilitation exercise is a virtual version of the commercially-available individual finger exerciser, Digi-Key. A 3-D model of the Digi-Key was created using Autocad Release 12 (Autodesk, 1994). This model was ported into our virtual environment and its dynamics were programmed. Since RM-I does not provide a user with force feedback to the pinky, and the original Digi-Key does not exercise the thumb, the Digi-Key model was modified so that the thumb is exercised. Several Digi-Keys were color coded to match the commercially-available models of different levels of maximum force. Thus the patient has a choice of different levels of rehabilitation, as illustrated in Figure 6-a. The patient can select a particular Digi-Key by touching it with the virtual hand depending on the finger forces determined by the physician or therapist. Again, the forces experienced by each finger are recorded and can be viewed at a later time. In this way a physician can have access to a patient's exercise routine and judge his/her progress without actually having to be present during the exercise itself. After looking at the graphs, the therapist can also judge whether the routine was performed in a satisfactory fashion (i.e. if all the fingers were exercised).

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Place Figure 6 about here

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The third, and last, exercise involves the patient's visual-motor coordination. A virtual model of a board with nine holes was created. The user has to perform a peg-in-hole insertion task, as shown in Figure 6-b. A WorldToolKit routine which checks for intersection of bounding boxes of objects was used to determine the collision of the peg with the board and its placement into a hole. When the exercise is started, the user can choose between three levels of difficulty – "Novice," "Intermediate" and "Expert." Each level has a different amount of time allowed for the user to complete the exercise. Clearances between the peg and hole also change from level to level, being smallest for the "Expert." At the end of the exercise the GUI tells the patient how many holes were filled, how much time was spent doing it and how many mistakes were made. A mistake corresponds to a missed hole or an attempt to put two pegs in one hole.

4 Database Integration

A system called "Hand Diagnosis and Rehabilitation" (HDR) has been designed using the Oracle engine. It allows the user to manipulate data through a user friendly, icon-based, interface. HDR consists of three modules - "Action," "Form" and "Report" (see Figure 7).

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Place Figure 7 about here

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The "Action module" is responsible for executing all the diagnosis and rehabilitation exercise operations and for storing all the data that is generated by these operations into the database for later use. When a user chooses one operation, that action is activated by the Action module as a procedure specific to that operation. When the operation is completed, the procedure passes all the data on to the database which stores it under the patient's name.

The "Form module" is responsible for providing the graphical interface which allows a user to enter, query, update, browse or delete data. This module was implemented using the Oracle Form tool (which provides various report templates) and is composed of two forms, the "patient entry form" and the "HDR data form." The relationship between the two forms is a natural reflection of the patient-operation relationship. The patient entry form is the core around which the rest of the modules are integrated. This form displays a screen for all patient attributes (name, address, etc.) and allows the user to either add a new patient to the database or query data on an existing patient. The "list" button on the form is used to launch a list-of-value dialog box which lists all the patients currently in the database so that a user can find a patient conveniently. The "down" button will pop up the HDR data form. In this form, the user can view all the operations done by the patient. To see what the graph output of an operation looks like, the user chooses the field and then clicks on the "graph' button. The form then displays the graph. For example, a force exertion graph displays the output of a dynamometer grip strength test.

The "Report Module" is activated by the "report" button. It is used to preview or print a report corresponding to the current patient and procedure. This module is implemented using the Oracle Report tool. This tool can be used to design various report templates. What is seen on the screen in preview mode is exactly what is printed on paper. Figure 8 shows a typical screen output. A typical report would contain all the data relevant to a particular patient, including all the diagnostic tests he/she has undergone, graphs of exercise routines showing progress that the patient has been making, comments or observations of the physician, or the physical therapist, etc.

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5 Discussion

The system presented in this paper uses digital input tools for hand diagnosis and a force feedback glove for exercising in a virtual environment. The system is safe and intuitive to use, and has been installed in a hand surgeon's physical therapy program. The difficulties with the calibration of the tactile Glove made impossible testing on patients Further evaluation in a clinical setting should be a true measure for the usability and usefulness of the system. Feedback from these trials will be used to incorporate modifications as suggested by the physician and the hand therapist. One possible enhancement is the addition of remote parameter change in the exercise routine, as well as remote data access and patient records consultation using a modem and telephone line.

We plan to periodically monitor remotely, the exercises performed by the patients and change their level of difficulty. This is a feature that may have a wide usage in future rehabilitation systems and will open the door for wider access to health care without having to leave one's home.

6 Conclusion and Future Research

An integrated system for hand diagnosis and rehabilitation has been developed. The basic functionality of the system was tested in our laboratory environment and is now being tested in the clinical field. The diagnostic component uses standard electronic instruments connected toa graphics workstation. A new approach to hand rehabilitation was presented using Virtual Reality simulations. This is viewed as an excellent tool for hand rehabilitation since it is multi-modal and could make a rehabilitation routine interesting and challenging for the patient. The diagnosis and rehabilitation systems are linked through a single user interface which is built on top of a single database. While the concept is intriguing, only the results of clinical trials will validate our expectations of improved diagnostic and rehabilitation outcome through the use of virtual reality.

Acknowledgments

Work reported here was supported by grants from the Whitaker Foundation, from Greenleaf Medical Systems and from the CAIP Center at Rutgers University with funds provided by the New Jersey Commission on Science and Technology and by CAIP industrial members. The authors would like to thank Daneca DiPaolo MD. and Melisa Kanter OTR for useful suggestions for the design of rehabilitation exercises. Further thanks go to Emmanuel Pere for his help in creating some of the virtual models.

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List of Captions

Figure 1: Unified hand diagnostic and rehabilitation system [Burdea, 1996].

Figure 2: Tactile Glove prototype: a) location of UFS sensors; b) sensor construction detail.

Figure 3: The Tactile Glove Interface [Burdea et al., 1995-b].

Figure 4: The C++ Class Hierarchy

Figure 5: Flowchart for a WorldToolKit Application

Figure 6: Sample rehabilitation exercises: a) using a virtual DigiKey; b) using a virtual peg board assembly.

Figure 7: The layout of the patients' database

Figure 8: A typical patient database screen

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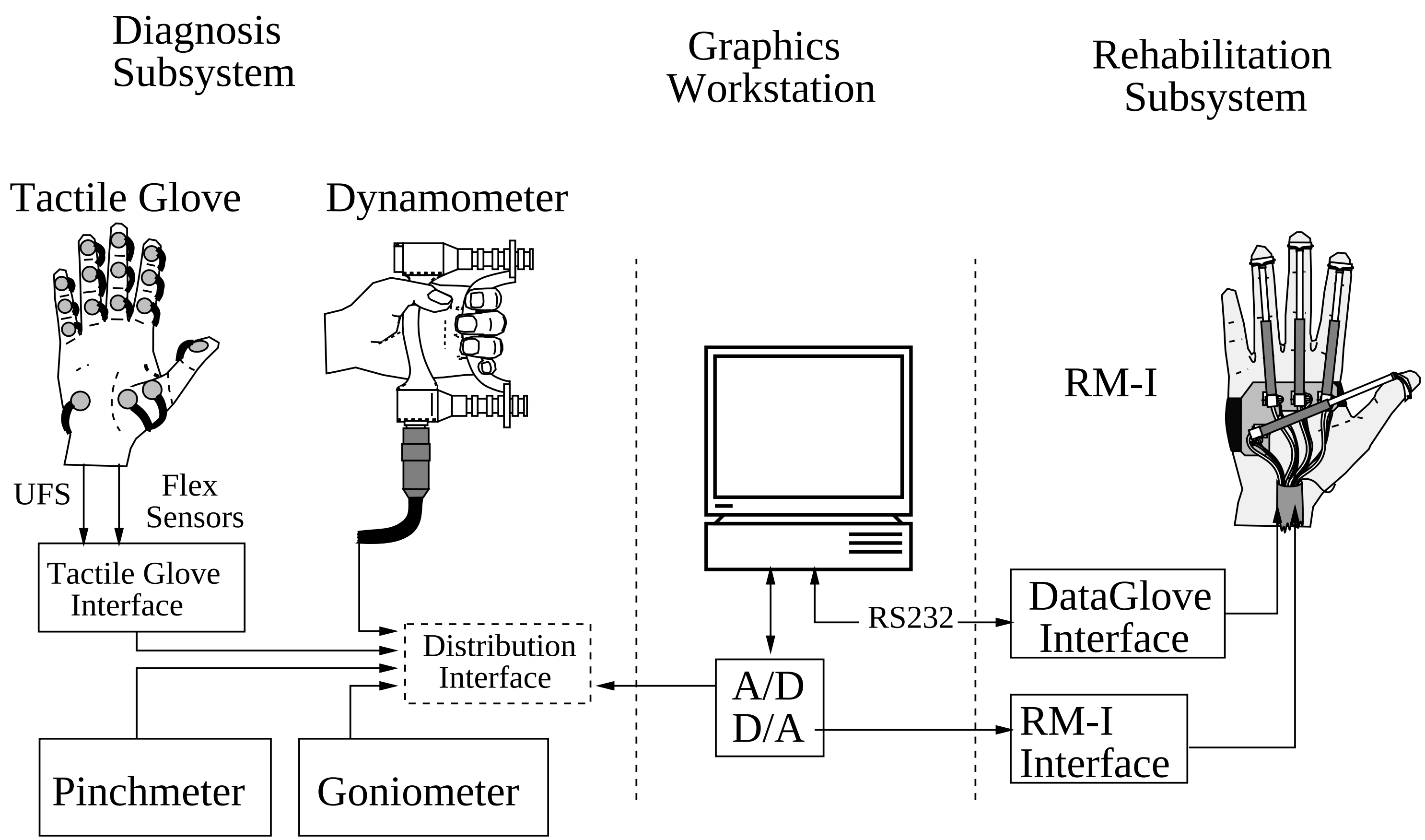
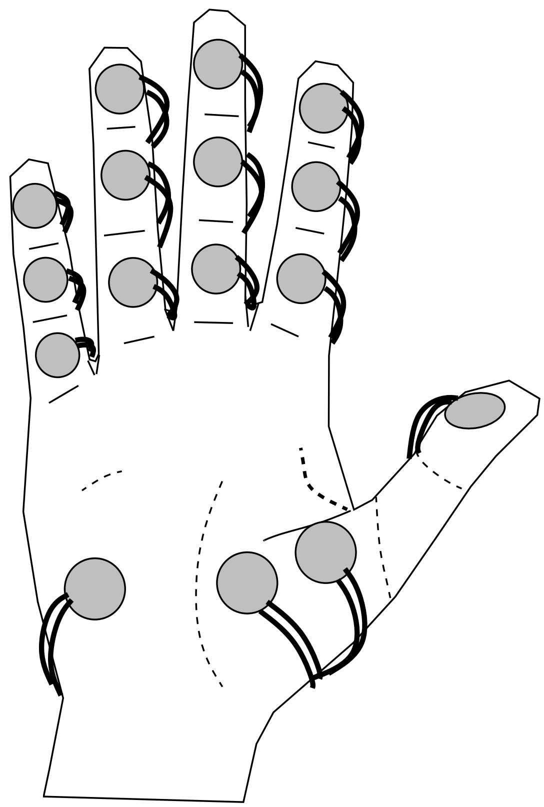

Diagnosis Subsystem
Graphics Workstation
Rehabilitation Subsystem
Tactile Glove
Dynamometer
RM-I
UFS
Flex Sensors
Tactile Glove Interface
Distribution Interface
A/D D/A
RS232
DataGlove Interface
RM-I Interface
Pinchmeter
Goniometer



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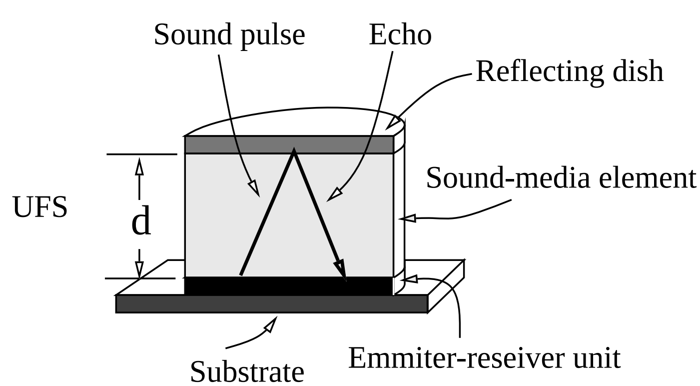
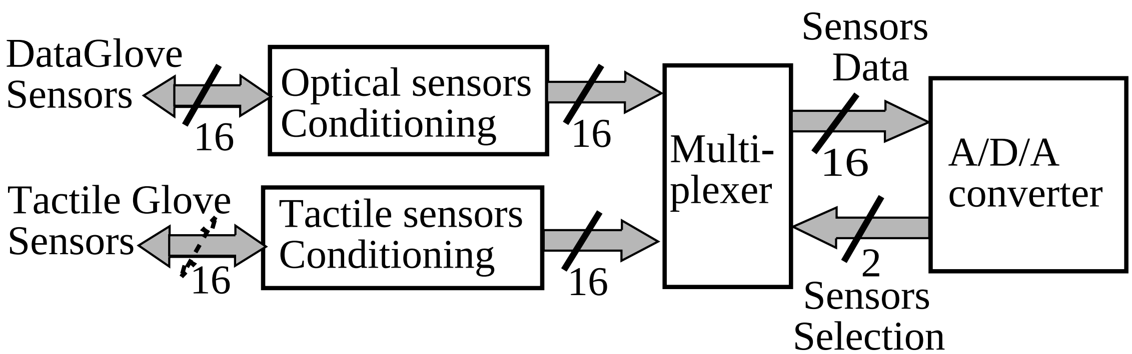


Sound pulse
Echo
Reflecting dish
Sound-media element
UFS
d
Substrate
Emmiter-reseiver unit

b)


DataGlove
Sensors
16
Optical sensors
Conditioning
16
Tactile Glove
Sensors
16
Tactile sensors
Conditioning
16
Multi-
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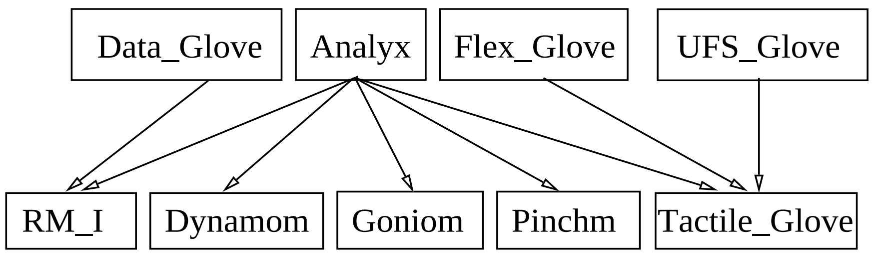
Sensors
Data
16
A/D/A
converter
2
Sensors
Selection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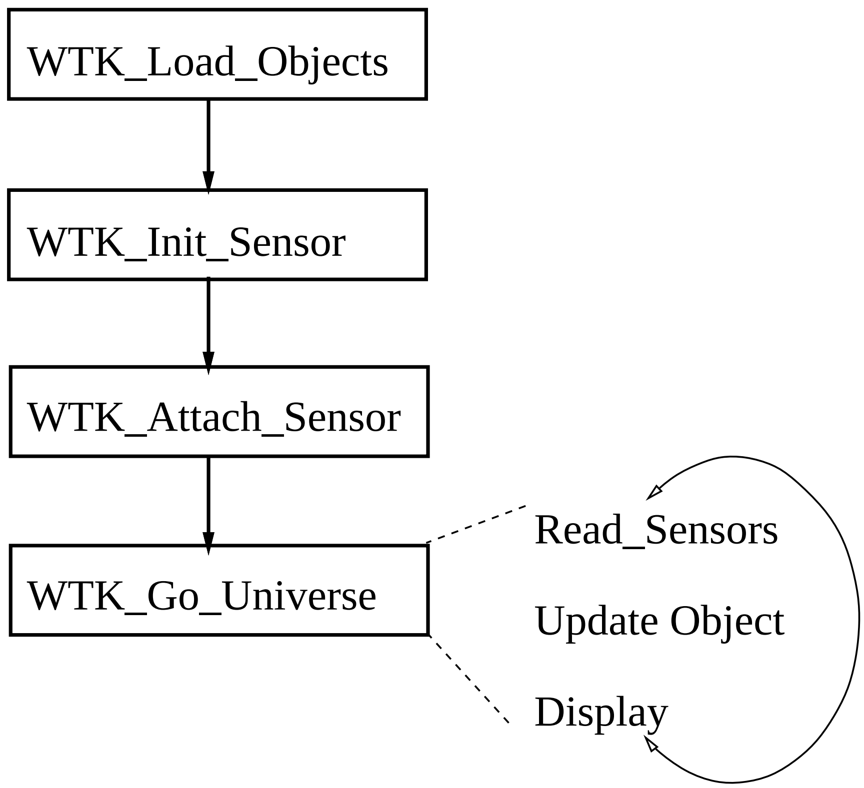
Analyx
Flex_Glove
UFS_Glove
RM_I
Dynamom
Goniom
Pinchm
Tactile_Glove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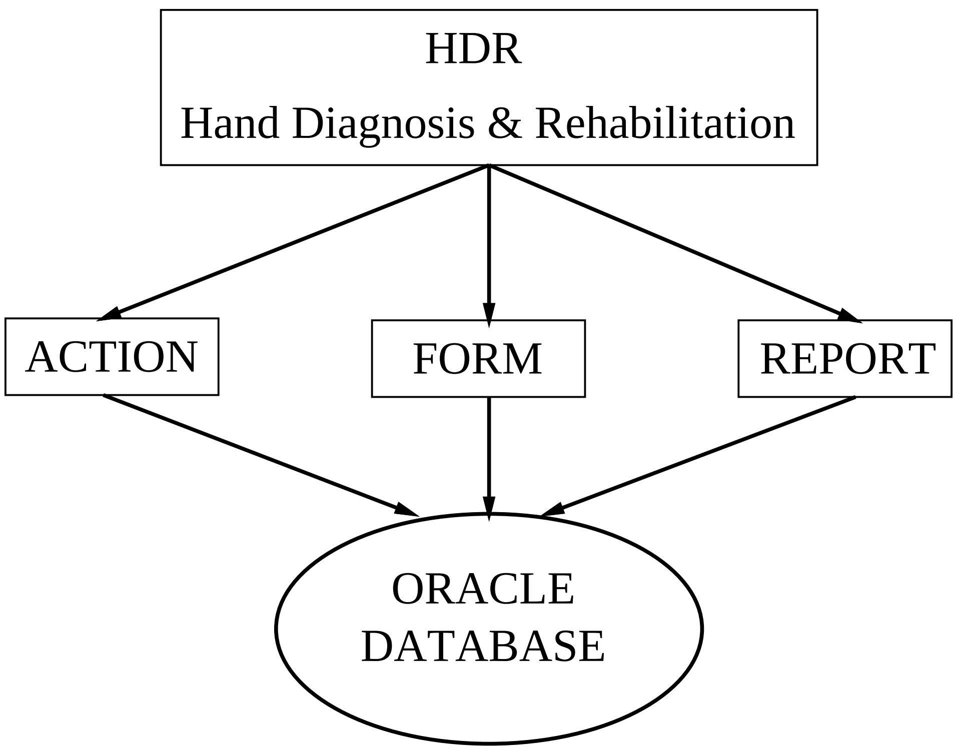
WTK_Init_Sensor
WTK_Attach_Sensor
WTK_Go_Universe
Read_Sensors
Update Object
Display


HDR
Hand Diagnosis & Rehabilitation
ACTION
FORM
REPORT
ORACLE
DATABASE

HAND MODEL	ASYNCHRONOUS PROTOCOLS		
	LOW-LEVEL	SHAR-MEM	WTK_SERIAL
1500 POLYGONS	5 fps	10 fps	11.5 fps
200 POLYGONS	8 fps	16 fps	14 fps