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EXOS RESEARCH ON MASTER CONTROLLERS FOR ROBOTIC DEVICES

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1 ABSTRACT

Two projects are currently being conducted by EXOS under the Small Business Innovation Research (SBIR) program with NASA. One project will develop a force feedback device for controlling robot hands, the other will develop an elbow and shoulder exoskeleton which can be integrated with other EXOS devices to provide whole robot arm and hand control. This paper will cover the project objectives, important research issues which have arisen during the developments, and interim results of the projects.

The Phase I projects currently underway will result in hardware prototypes and identification of research issues required for complete system development/integration.

2 INTRODUCTION

There has been a significant amount of research on robot hands (Salisbury, 1985) and force reflecting controllers (e.g. Bejczy and Salisbury, 1983, Agronin, 1987) for robot arm manipulation. The Stanford/JPL 6 DOF hand controller is an example of a compact non-antropomorphic force reflecting arm master. There have been a variety of anthropomorphic or semi anthropomorphic force reflecting masters for hands or arms (review in Iwata 1990) but little work has been done to integrate manipulation and sensing for teleoperation of dexterous robot hands and arms together. One complete system (Jacobsen 1989) employs an anthropomorphic configuration which is bulky, is not compatible with the field environment, and is very expensive. In addition there are many research issues which arise in the design and development of these devices which have not been addressed in the literature to date.

Very few force reflecting sytems have been developed for generating forces on the individual fingers and the palm. Iwata (Iwata 1990) describes a system for the thumb, two fingers and the palm. The palm is actuated by a six degree-of-freedom parallel stage driven by electric motors. Each of the two fingers and thumb has single degree-of-freedom motion and is also driven by electric motors. This system can transmit large forces to the hand and fingers, but is limited to pinch type grasps because of the single degree-of-freedom plates for the fingers.

Burdea, Zhuang, and Roskos (1991) describe a system based on pneumatic cylinders and the VPL dataglove. This sytem uses pnumatic cylinders placed between the inside of the palm and the fingertips to generate forces. The system is compact and light, but at present can only simulate grasp forces between the palm and the fingertips. Contact of the fingers with objects supported externally cannot be simulated.

The current EXOS projects are the first steps towards building a comfortable, lightweight, field compatible and affordable integrated anthropomorphic force feedback master for teleoperation of dexterous robot hands and arms. This process of development, by necessity, includes answering some basic research questions regarding human capabilities, limitations, and perceptions. This paper will report on progress to date towards these objectives.

3 SENSING AND FORCE REFLECTING EXOSKELETON (SAFiRE) PROGRESS

This program is intended to result in the design and development of a sensing and force reflecting exoskeleton (SAFiRE) which provides control signals to robot hands and force feedback to the human operator. The SAFiRE will allow robot hands working in unstructured environments to gently touch objects, and finely manipulate them without exerting excessive forces.

3.1 Phase I Project Objectives

The goal of the Phase I effort is to build a 2 degree of freedom (DOF) prototype SAFiRE which demonstrates the feasibility and utility of a SAFiRE in controlling robots.

3.2 Initial Design Goals

We surveyed the relevant literature, discussed the overall objectives an developed a set of screening criteria for the designs we were developing Each of the members of the design team then ranked the criteria. The results were that comfort, ease of use and feel were considered to be the most important criteria. The criteria and their rankings are given below.

3.3 Specifications

We then spent some time attempting to develop and quantify specifications for the details of the device. Some of the key areas have little available information on the performance required in order to achieve the design goals. In these cases the consensus was to examine systems which have been built, how they performed, and how similar the application they were used in is to our application. From this type of analysis we can make a best guess specification which can be revised as the program progresses and hardware is available for conducting experiments.

The following is a preliminary specification for the SAFiRE. The 2 DOF prototype will meet a subset of these specifications.

1. Hand Size: 50th %ile female to 95th %ile male

2. Joints:
   DOF: 10 with force reflection, others with

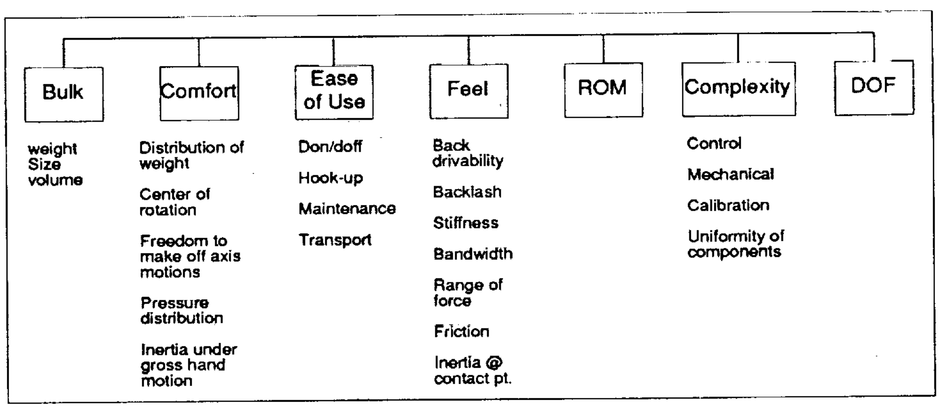

Figure 1: SCREENING CRITERIA

RANKING

CRITERA	RANK	SCORE	PERCENT
FEEL	1	17.66	25.0
COMFORT	2	16.15	22.9
EASE OF USE	3	11.94	16.9
BULK	4	9.92	14.1
COMPLEXITY	5	8.81	12.5
ROM	6	3.00	4.3
DOF	7	3.00	4.3

position only Range of Motion: 120o maximum for an individual joint Angular Resolution: ~1/2o

3. Force Reflection:
   Direction: Both Flexion and Extension
   Magnitude: 4 lbf-in Peak torque at MP joint 2 lbf-in Continuous

4. Dynamic Performance:
   Friction: Less than .25 oz-in
   Backlash: Less than .20°
   Frequency Response: 3Db point at ~50 Hz

5. Weight:
   Exoskeleton: 1/2 oz. Per DOF
   Actuators: mounted on forearm ~1 oz. Per actuator

These specifications will be used as a guideline to compare concepts. As we develop prototypes and conduct experiments we will be able to refine these specifications.

3.4 Design Options

In developing a design which fits the screening criteria a variety of concepts for transmission and actuation were considered. The following charts describe these options:

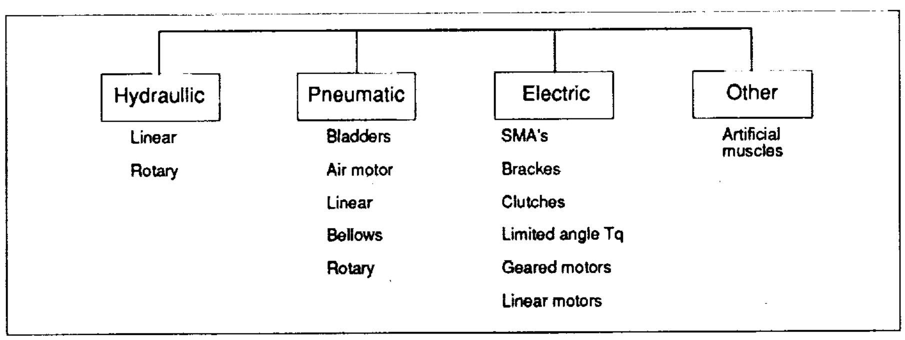

Figure 2: ACTUATION OPTIONS

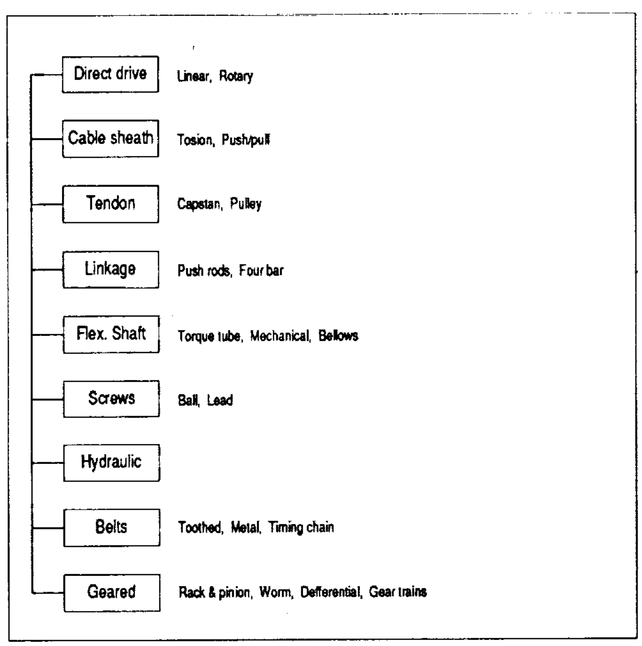

Figure 3: TRANSMISSION OPTIONS

Several overall concepts for the system configuration were developed and used to evaluate the actuation and transmission concepts. Mock-ups and bench top experiments were performed to assist in the process of determining which options were feasible. A 2DOF working prototype of the resulting design is currently being detailed and constructed.

3.5 Research Issues

A number of issues were identified which were not covered adequately enough in the literature to permit the results to be used in developing screening criteria, specifications and finally designs. Specific areas of research needs include:

Types of Feedback
- -tactile
- -kinesthetic (force)
- -auditory

Feedback
- -intensity
- -location
- -transitions

Grounding
- -to the hand
- -to ground
- -to other body parts

The types of specific research projects that will help to resolve these issues include:

When designing any force feedback device the objectives in terms of the desired bandwidth, force output, gain, and resolution must be determined. To determine the bandwidth required one must look at the task and determine what objects need to be manipulated, their stiffness and other mechanical properties, but one must also determine the range of stiffness of the finger (for feedback to the hand) and other mechanical properties of the hand and arm. The properties of the hand and arm vary from person to person, but they also vary based upon the state of the different muscles being used.

Imagine how it feels when your arm is locked with all its muscles contracted when your arm strikes an object as compared with the feeling associated with a completely relaxed arm encountering an object. Consider the example of arm wrestling. If your muscles are contracted when the competition begins it requires a much larger force to move your arm than if they are relaxed. Imagine the differences in the design of a arm wrestling telerobot if the competitor always had relaxed muscles versus one which had to deal with contracted muscles, or what about the more realistic case where the exact conditions of the competitors arm are unknown. To size the motors, set their required response time and many other factors the range of human responses to force feedback must be known.

To develop the transmission, actuation, and control principles the amount of perceptible friction and backlash must be quantified. The human brain is able to learn, and adapt very readily to variations between the real object and the simulated one in certain cases without perceiving the difference. But which types of departures are acceptable and how much deviation from the exact physical conditions to be simulated is possible without reduced performance needs to be studied. For example, virtually all mechanical mechanisms which are practical for feedback to the hand have some friction. If the feedback device is being operated in a free motion mode (i.e. the simulated hand is not touching any objects) the operator will perceive that friction as a feeling of touching an object. The large the friction the harder the object will be perceived to be. For different parts of the hand and body as a whole, the level of perceptible friction (i.e. friction induced force) is unknown. In addition the inertia of the device will feel like an object.

Very little work has been done on the ratio of the force at the master to that of the slave. This ratio is very task dependant. For example a robot (or virtual robot) which can lift a 1000 pound payload clearly does not want to feedback all that force to the operator. On the other extreme, in a microsurgical application the level of force required to make a tiny incision may be beneath the level of perception of the human hand, therefore in this situation the force must be amplified. Some situations require both extremes and thus the issue of transitions must be considered. In addition when scaling the force different phenomena may need to be scaled differently. For example, if you do microsurgery the major things that you may want to feel could be surface tension and drag which are not felt at all a human scale. Therefore a strategy for the representation must be studied and developed for each application.

No known studies have been found which address the issues associated with perception of force as it relates to where the device is grounded. Most developers of feedback hardware have just decided to ground it to external ground or to the hand. We conducted some crude experiments in conjunction with this program which told us that grounding the device to the arm has the potential to provide realistic feedback within certain constraints. It is necessary to understand how to use grounding to optimize task performance.

Auditory feedback has been used to assist in providing a more realistic work environment. Only anecdotal reports of accidental improvements in performance due to auditory feedback of, for example, motor torques has been reported. A systematic study of auditory feedback to determine when it is appropriate, how to use it effectively, and how much of a performance improvement it provides in different task situations should be conducted.

Little work has been done to evaluate where tactile feedback could be best used, the type of information to be presented and how it works in combination with force and auditory feedback.

In the initial phase of this project we have conducted some preliminary experiments on these issues and will be better able to study them once the Phase I prototype is completed.

4 EXOSKELETAL ARM MASTER (EAM) PROGRESS

The exoskeleton arm master (EAM) program will result in an elbow and shoulder measurement system which will provide precise measurement of the arm and forearm motion. The system will be portable and comfortable to wear, thereby allowing free movement of the operator without loss of control or precision in robot arm position.

4.1 Phase I Project Objectives

The goal of the Phase I effort is to build an EAM which demonstrates the feasibility and utility of an EAM in providing integrated control capabilities for whole-arm manipulation and grasping.

4.2 Arm Kinematics

The human body is a complex linkage with many small motions in addition to the major joint motions which make the task of attaching an exoskeleton to the arm comfortably while obtaining accurate, reliable and repeatable measurements of joint motions difficult. The seven basic human arm motions which must be converted into robot control signals are illustrated in Figure 4.

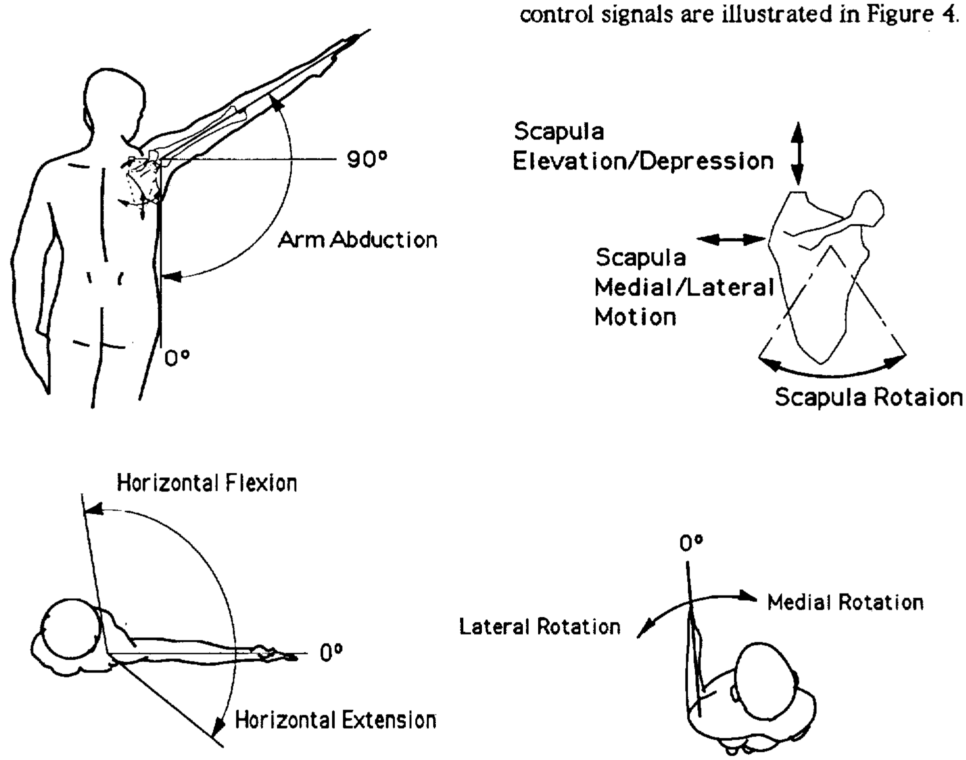

Figure 4. Major shoulder movement. (after Kapandji I.A.)

4.2.1 Shoulder

The shoulder is a complex structure which involves a combination of motions from several joints (Figure 4.). For a sample, arm abduction as shown in Figure 4., uses the glenohumeral joint to provide motions during the initial portion of the range of motion. Once the arm moves past the horizontal position, shoulder shrugging (Scapula elavation and rotation) is employed. In addition the scapula has medial and lateral movement. Robot arms do not typically have these motions. Therefore in developing an exoskeleton master for controlling robot arms the motion must either be transduced, filtered out, or used with a method of transforming the motions into robot arm motions.

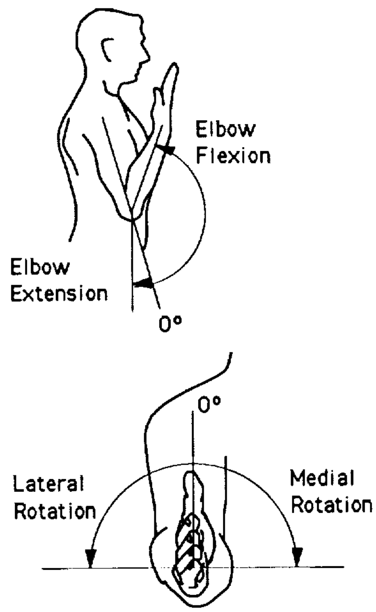

Figure 5. Major elbow motion.
(after Kapandji I.A.)

4.2.2 Elbow

The elbow and forearm have two degrees of freedom which must be measured. Elbow flexion is a straight forward motion with only a small amount of motion of the joint center of rotation to be accommodated. The challenge in this joint is how to comfortably and accurately attach to the body to follow this motion. It is even more difficult to address attachment with respect to the supination/pronation because this motion is accomplished by the radius pivoting around the ulna

4.2.3 Wrist

The wrist has two degrees of freedom which must be measured. In addition the wrist has several small motions which make it difficult to transduce the major wrist motions. The center of rotation moves, the two motions are coupled in some ranges and the configuration of the bones to which one must attach changes with motion. The EXOS GripMaster™ transduces wrist flexion/extension and radial/ulnar deviation. It uses the patented Dexterous HandMaster™ passive pivots and general linkage configuration to allow accurate tracking of these two motions.

Although the initial EAM prototypes will concentrate on the elbow and shoulder, the GM wrist and DHM hand can be used as is for completing the control.

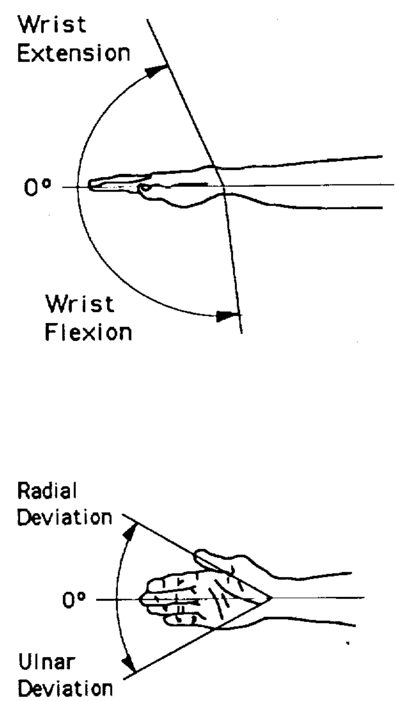

Figure 6. Major movement of the wrist.
(after Kapandji I.A.)

4.3 Required Ranges of Motion

Although the exact ranges of motion of the shoulder and elbow joints is some what controversial [An, Doody, Freeman, Inman, Lucas, Morrey, NASA-STD-3000, Steindler and Youm]. The following table summarizes the commonly cited data from medical literature and those published by NASA. Those starred must be transduced for robot control.

The fewer sensors a given design has the lighter it will be and lower the inertia. However, since it is not possible to make the axes of motion of the human joint align exactly with the axes of motion of the exoskeleton for all users with a small number of sensors the computation required to transform the sensor readings into human joint angles increases. Therefore trade-offs were conducted among these factors to arrive at an initial design configuration.

JOINT MOTION	NORMAL ROM†	SUITED ROM††
Shoulder Abduction/Adduction*	150°	150°
Shoulder Media/Lateral Rotation*	130°	120°
Shoulder Horizontal Flexion/Extension*	170°	150°
Scapula Elevation/Depression	10-12cm	N/A
Scapula Medial/Lateral Movement	15cm	N/A
Scapula Rotation	60°	N/A
Elbow Flexion/Extension*	145°	130°
Forearm Supination/Pronation*	180°	180°
Wrist Flexion/Extension*	170°	N/A
Wrist Radial/Ulnar Deviation*	60°	N/A

† Kapandji I.A. (1982)
†† NASA-STD-3000. (1989)

4.4 Concept Development

Once the human motions are known the task of determining the optimal linkage to follow these motions must be determined. There are several competing design considerations that were identified in the process of developing concepts. They are:

- minimization of number of sensors
- minimization of computation complexity
- Low inertia
- rigidity of attachment
- comfort
- ease of donning/doffing
- adjustability to accommodate human variability
- range of motion
- safety

4.5 Testing

In order to test the ability of the EAM to measure the human jointsaccurately, an additional accepted method of measuring the human joints is required. There is no "gold standard" for human motion measurement. Data derived form video or other optical techniques rely on placing markers on the surface on the body. This method has inherent errors due to skin motion and shape changes in the limbs due to muscular contraction. X-ray data can tell you where the bones are, but without placing radiopaque markers in the bone correlation of one view with another has significant errors. Therefore we decided to begin with a known motion which was produced by building a shoulder simulator. This device is simply three high precision potentiometers with bearings (0.1%

linearity) to ensure the highest repeatability possible with off the shelf components. These were mounted such that their axes of motion coincide and correspond to the three primary shoulder degrees of freedom. Provision for rigidly attaching the EAM to the shoulder simulator was also made to eliminate another factor affecting the measurements in the real world, motion artifact due to motion of the attachments. A schematic of the device is given below.

Thus various kinematic configurations and algorithms for transforming the measured angles to human joint angles can be tested against a "gold standard." A similar device is being constructed to test wrist designs.

5 CONCLUSIONS

Currently the feasibility demonstration prototypes for the SAFiRE and EAM are being built and tested. An array of research issues and design trade offs have been identified and initial estimates to resolve these issues or conduct trade-offs have been made to develop the first level prototypes. Once these devices are complete testing will be required to determine how well these devices meet the design goals and to identify areas requiring more detailed research and development to produce fully functional devices.

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