DOD Sample Phase II Proposal

ADVANCED DEVELOPMENT OF NEXT ACTUATORS FOR HUMAN SENSORY FEEDBACK

TOPIC NUMBER: A92-023A

PROPOSAL TITLE: ADVANCED DEVELOPMENT OF NEXT ACTUATORS FOR HUMAN SENSORY FEEDBACK

FIRM NAME: TECHNICAL RESEARCH ASSOCIATES, INC.

ABSTRACT

The development of actuators with enhanced capabilities is critical to the achievement of sensory feedback systems for intuitive, real time human operations of telerobotic systems. The objective of this research project is to continue development of new actuators using active materials which will enhance the capabilities of dexterous, exoskeletal feedback systems for telerobotic applications. In Phase I, feasibility of novel Terfenol-D driven actuators was demonstrated. The new actuators are efficient, responsive, small and exert relatively high forces. The actuators provide proportional forces and are easily interfaced with digital electronics because of low voltage requirements. Phase II will pursue advanced development of proportional force resistive brake actuators and active linear actuators. The actuator designs will be optimized, fabricated and integrated into a digitally controllable exoskeleton demonstration test bed.

Commercial, small, light weight, responsive actuators could find application by military and commercial entities for telerobotic applications. The completed devices could also be used as actuators in a number of automated mechanical systems found in home , office and industrial environments.

KEYWORDS:

- Actuators
- Robotics
- Exoskeleton
- Active Materials
- Terfenol-D
- Force Feedback
- Magnetostrictive

(The sections above are on the Cover Sheet)

Identification and Significance of the Problem or Opportunity

The integration of human control and robots has demonstrated advantages effected by combining the cognitive capabilities of the human with the strength and durability of robots. The human is given the ability to operate real time in lethal and hazardous conditions by remotely controlling the manipulation of the robot. Significant effort has been expended in developing robotic end effectors, sensors and exoskeletons to control the motions of the robotic arms. Human sized robotic hands have been developed which can effect fine manipulations. For intuitive control and fine manipulation, small light weight exoskeletons with force feedback actuator mechanisms are needed to enhance operator awareness.

This Phase II project will adapt Terfenol-D magnetostrictive technologies to actuator mechanisms useful in sensory feed back systems. Magnetostrictive materials are materials which change shape when exposed to magnetic fields. Magnetostrictive materials have been available for over a century and came into common use in the 1950's with the use of nickel-based alloys. These alloys were limited to strains in the order of 50 ppm. The discovery of piezoceramics improved this with strains of approximately 250 ppm. Discovery of Terfenol-D a relatively new magnetostrictive material improved on the magnitude of the achievable strains as compared to previously available magnetostrictive materials by a factor of 40 times or about 10 times that of piezoceramics such as lead titanate zirconate (PZT). The Terfenol-D material was discovered during research into sonar by the U.S. Navy. Terfenol-D is an alloy of terbium, dysprosium, and iron. Actuators based on Terfenol-D have been shown to transmit large amounts of energy in a small volume and are highly efficient. The Terfenol-D systems require relatively low intensity magnetic fields, and can operate at low voltages compared to piezoceramics. The new alloy is being applied to many applications which have been previously accomplished by piezoceramics. Piezoceramics are brittle while the Terfenol material demonstrates a high modulus. The material has a rapid response time (5KHz) unlike shape memory alloys such as Nitinol.

Force Feedback

For human controlled robot manipulators, the ideal would be to produce a human, remote robot system wherein the human is presented with the same sensations that he would have if he were doing the job directly, and to have a robot (Slave) that precisely matched the motion of the human (master). By precisely it is meant that not only does the Slave move to a point in space controlled by the Master, but that it moves there at the same time and with the same speed as the master and that it provides a force that is sensible to and controllable by the Master. Anyone who has tried to work with thick gloves on will recognize how much we depend upon kinesthetic feedback for control of our physical actions. Research has shown that task speed and other performance measures are increased significantly when kinesthetic feedback is added to the visual feedback that is usually employed.

A force feedback system requires that the Slave have the ability to sense the forces that are to be recreated for feedback to the Master. This is done with sensor transducers. This information must then be converted to replicate forces through the use of Actuators that convert the signal from the sensors into appropriate forces. The forces of the actuators then must be transmitted to the human through some mechanical coupling mechanism. Unless this structure is surgically implanted into the human, it must of necessity be outside the body and is therefor called an exoskeleton meaning a structure connected to the body but external to it.

The development of new light weight efficient actuators are needed to provide intuitive feedback to human sized exoskeleton controls by providing realistic forces reflected from the object being manipulated. A carefully designed dexterous, intuitive feedback system could be interfaced with microscopic robots with feedback amplification, human scale robots with actual forces or manipulate large robots with force signal attenuation.

Actuators

Actuators may be characterized as resistive or active. These basic elements may be combined into a single Hybrid device. If the actuators are electromechanical as is the case for the proposed magnetostrictive devices then their behavior may be electronically controlled. If the control logic becomes sufficiently complex then we will call programmable actuators.

The resistive actuator does not initiate any motion; its function is to resist motion. Examples of resistive actuators are pressure plate clutches and viscous fluid shock absorbers. A clutch resists the relative motion of two structures by providing a resistance to slippage between the structures. In a pressure plate clutch, the resisting force is related to the plate pressure applied to squeeze the surfaces together and to the characteristics of the rubbing surfaces which can be lumped together into a coefficient of friction. In the case of a hydraulic shock absorber the behavior of the actuator is controlled by the surface area and shape of the piston and by the viscosity of the resistive fluid.

The simplest active actuator is a lever, where a force and motion on one side of the lever appears as a smaller motion and greater force on the other side. The ratio of the lifting force divided by the applied force is the leverage, (also gear ratio, mechanical advantage, or impedance ratio). If we add a clamping mechanism to our machine, we can build a linear motor. One example of a simple linear motor is the automobile bumper jack. When we get to the end of the range of motion of the jack handle the device is clamped while the handle is returned so that the action can be repeated. In order for the device to operate at its maximum force, the clamp strength must be at least as strong as the lifting strength. If the clamp strength is less than the active strength then the device will be limited by the clamp. In the case of the mechanical jack its input impedance is represented by the weigh that is required to move the jack handle (for an electrical actuator the impedance is related to the electrical voltage required to operate the device). Each time the handle is cycled the jack will move a small amount. The lifting speed will be this distance times the number of times per second that the handle is pumped. The pump rate may be expressed as a frequency . The range of frequencies from the lowest to the highest is called the band width.

The Position of the jack can be determined by multiplying the distance moved in a single stroke times the number of strokes plus any partial stroke at the end. The total range of motion is the total distance that the lifting part of the jack can move. If there is any looseness in the system then when the direction of travel is reversed the handle will travel for a distance before the actuator will move; this is called backlash. The whole jack will have a mass. If we divide the maximum weight that the Jack can lift by the mass of the jack then we will have a measure of force/mass mass specific force . If the total volume of the jack is measured we could compute force / volume of volume specific force. The work done by the jack is the weight moved by the jack times the distance moved and the power is the work done divided by the time taken to do the work. Finally mass specific power and volume specific power can be computed by dividing power by mass and volume respectively. The energy efficiency is the ratio of the input energy divided by the work done by the actuator. These are all characteristics that must be considered in designing and specifying actuators for real applications.

One other common type of actuator is typified by the spring. For a spring type actuator the force produced by the actuator is related to the compression of the spring. The force produced by a spring divided by the distance that the spring is compression is the stiffness or spring constant. A generalize actuator of this type is one where the actuator force is a function of position.

Actuators of several types may be combined in a variety of ways to produce actuators with complex behavior. Tasks involving the manipulation of real objects will encounter complex forces that could require hybrid programmable actuators for their faithful replication.

The development of new actuators is critical to the achievement of sensory feedback systems for intuitive, real time human operation of robotic systems in hazardous or otherwise restrictive environments. To be truly intuitive, the actuators should provide responses of appropriate force with frequencies in the kilohertz range.

Phase I Results

The Phase I SBIR project studied and demonstrated the feasibility of Terfenol-D magnetostrictive actuators as they might be applied to telerobotic actuation. The project has come to grips with the practical constraints implicit in the development of these new technologies thus laying a good foundation upon which this Phase

II project can be successfully implemented. Phase I demonstrated the general feasibility of the concepts and illuminated the technical hurdles to be crossed during advanced device optimization. The principal investigator is confident that refined actuators, based on the proposed magnetostrictive Terfenol-D materials, will be important elements in future robotic and automation systems.

The devices fill a need not only for telerobotic exoskeletal systems but also for numerous engineering automation systems. There are essentially two areas of research that need attention. First, the theoretical study and modeling of individual physical parameters as they apply to device concepts and configurations need to be continued. Secondly, the actual implementation of prototypes is important in order to evaluate theoretical constructs and to come to terms with the practical methods and materials for fabrication of these relatively high precision devices.

At the completion of Phase II the technologies will be readied for transfer to the commercial market. It is envisioned that a family of actuators will be made available as independent modules. These modules would be well specified and function for specific force ranges. The device would be made available for integration by other commercial entities and for in house integration into virtual reality exoskeletal products and feedback systems to be manufactured by TRA.

Technical Objectives

The objective of this project is to develop improved actuators for use in force feedback anthropologic master hands for the control of slave robot actuators and for other applications. This problem has been studied by others, however no adequate solution has been perfected . Based upon the findings and success of Phase I, we propose to develop actuators based on the newly available magnetorestrictive material Terfenol D. By necessity, we will have to concern ourselves with sensors and exoskeleton design in order to functionally test the new actuators. The following is a summary of the Key Tasks planed for Phase II.

TASK 1. System Review

Will refine specific end product requirements desirable to successfully carry this development through to Phase II commercial application.

TASK 2. Resistive Actuator Development

Will consider various alternative designs for resistive type actuators that are capable of meeting the task I specifications. One or more specific device(s) will be designed produced and operational specifications verified.

TASK 3. Linear Motor Development

Will be devoted to the design construction and calibration of an active actuator of the linear motor type and possibly of a of a Hybrid programmable actuator.

TASK 4. Application Simulation

The objective of Task 4 is to provide computer controlled simulation and exoskeleton test platforms for the calibration and functional testing of the actuators developed in task 2 and 3.

TASK 5. Documentation

Will produce the final report and other documentation. This documentation should specify the new actuators with sufficient precision that they can be specified and applied by engineers who are working on other robotics, controllers or adaptive structure developments.

Work Plan

The Phase II work plan is designed to continue the successful Phase I, proof of concept project through the production of useful new force feedback actuators for use in robotics and for other applications.

TASK 1. Specifications

TASK 1.1 KICKOFF MEETING

This task will begin with a kickoff meeting between the project team and the project officers. This meeting could be in SLC or some other location at the discretion of the project monitor. The purpose is to help the project team get a better understanding of USAF programs and requirements so that product development can be directed towards satisfying specific USAF needs and mission.

TASK 1.2 DESIGN SPECIFICATIONS

Actuator specifications will be developed for specific exoskeleton and actuator applications as discussed in the kickoff meeting.

TASK 1.2.1 DEXTEROUS MASTER

In addition actuator specifications for the specific requirements of a Force feedback dexterous master will be developed. For each actuator application it will be necessary to specify :

- range of motion
- degrees of freedom
- bandwidth
- force
- velocity
- maximum size
- maximum weight
- maximum heat dissipation
- geometric constraints
- other constraints

TASK 1.2.2 SLAVE SIMULATOR

This task will develop specifications for the simulators. These specifications will define the Slave that is being simulated, its repertoire of motions and a characterization of the forces that it would encounter in performing its tasks. They will also determine how these motions and forces would be detected and the nature of the transducer feedback signals that the master controller will have to except and interpret. This information will be compiled as a portion of the interface specifications for the actuator controller. Specifications for the specific mechanical fixtures and transducers that will be developed in Task 4 to provide functional test of the new actuators will also be documented.

TASK 2. Resistive Actuator Development

The object of this task is to develop one or more specific resistive actuators. The actuator(s) developed will be for the specific applications and designed to the specifications developed in Task 1. Task I proved the feasibility of using Terfenol D to achieve brake type resistive articulations. Because of the limited time and budget constraints of Phase I the prototypes developed were built using available materials and constructed to prototype tolerances. In order to develop a practical device, every aspect of he design will need to be optimized. By doing this it is safe to predict a factor of 10 or more in improvement over the Phase I prototypes.

TASK 2.1 ANALYTICAL MODELING

The analytical models for these devices will be improved to allow design alternatives to be simulated before actual construction. The model will take into account brake surface characteristics, device leverage, expected force range, power dissipation, and weigh, prestress, tolerances, thermal expansion and structural stability of the device housing. The project team has the expertise and computers available for this task. It would, however, be desirable to acquire additional mathematical simulation software such as “Mathematics” in order to facilitate the modeling.

TASK 2.2 CONCEPT DEVELOPMENT

Will be devoted to the exploration of variations of the actuator concepts demonstrated in Phase I and of related actuator concepts. Each promising concept will be modeled analytical and possibly prototyped. Improved designs will be sought for resistive actuators that respond to axial, linear and ball and socket type motions

In Phase I we prototyped actuators with analog control. Analogy control means that the force of the actuator is proportional to the current supplied to the actuator. During Phase II we will extent our scope to look at digital control. Because these devices can be turned on and off in a short time period (less than a thousandth of a second) it is possible to consider computer digital control where the actuator is turned on and off in computer generated pattern so that the device can made to exhibit a complex resistive force. For instance it can replicate a position brake, a resistance related to position, a resistance proportional to velocity (shock absorber), a controlled deceleration, etc.

TASK 2.3 CONCEPT SELECTION

Will select those actuators that will be perfected and tested. The selection(s) will be made in conformation to the requirements of Task I with consideration for the products that have the best prospect for Phase II commercialization.

TASK 2.4 PROTOTYPE DESIGN

Will complete the design and engineering of the specific devices selected in Task 2.3 . This will require mechanical design , magnetic circuit design, design of the drive electronics and control software. Each of these tasks will be directed to optimizing the specific performance of the device, i.e. reducing the size, weight, power requirement and increasing the bandwidth and dynamic range of the device(s).

TASK 2.5 PROTOTYPE CONSTRUCTION

Will be done in-house with the possible exception of a few high precision parts. The TRA machine shop is currently capable of performing most prototype work. If special machine work is required it will be purchased locally.

This task includes fabrication of the mechanical device, assembly of the drive electronics and development of control software. The robotics applications envisioned at this time will likely have a computer interface between the Master and Slave in order to track and translate commands and sensor feedback so it makes sense to put as much control logic as possible in the same computer. Terfenol-D materials are available from ETREMA and from EDO in Salt Lake City.

TASK 2.6 TEST/MODIFY

The actuators will be functionally tested to see if they meet the design specifications. We anticipate that there will be some iteration of tasks 2.6, 2.4 and 2.5 as the prototype is modified to improve its performance.

TASK 2.7 DOCUMENTATION

Test data will be analyzed and documented during this task. Device design documentation will be corrected to include any modifications made as a result the optimization process.

TASK 3. Linear Motor Development

The object of this task is to develop one or more specific linear motor actuators. The actuator(s) developed will be for the specific application and designed to the specifications developed in Task 1. Task I proved the feasibility of using Terfenol d. to construct a compact linear motor actuator. Because of the limited time and budget constraints of Phase I, the prototypes developed were built using available materials and constructed to prototype tolerances. In order to develop a practical devic e, every aspect of he design will need to be optimized. The linear motor concepts of Phase I will be improved and extended to include digital computer control.

TASK 3.1 ANALYTICAL MODELING

The analytical models for these devices will be improved to allow design alternatives to be simulated short of actual construction. The model will take into account brake surface characteristics, device leverage, expected force range, range of motio n, shaft speed, bandwidth, power dissipation prestress conditions, tolerances, thermal expansion and structural stability of the device housing. Issues of noise reduction will also be analyzed. The models will be used to optimize the mass specific and volume specific performance of the final device. The project team has the expertise and computers available for this task.

TASK 3.2 CONCEPT DEVELOPMENT

Will be devoted to the exploration of variations of the linear motor actuator concepts demonstrated in Phase I . Each promising concept will be modeled analytical and possibly prototyped. Improved designs will be sought. In Phase I we prototyped actuators with hard logic control that allowed for control of motor power and speed. A During Phase II we will extent our scope to look at general computer control of speed position and power. Because these devices can be turned on and off in a short time period (less than a thousandth of a second) it is possible to consider computer digital control where the actuator is turned on and off in computer generated pattern so that the device can made to exhibit a complex linear motion.

With the perfection of both an efficient programmable brake mechanism and an efficient programmable linear motor it is theoretically possible to incorporate both into a hybrid device that could simulate a generalized complex force. (within its streng th and range of motion limits). Designs that could take advantage of this possibility will be considered during this concept development task.

The linear motor drive lends itself to application as either a direct actuator or as a remote actuator that applies a force through tendons or hydraulic fluids. these variations will also be considered during this task.

Table 1 describes a proprietary concept for the creation of a hybrid controllable actuator capable of simulating an arbitrary complex force.

Table 1. Generalized Force

There are several different types of forces that could contribute to a general force:

1. Forces that are related to position (x):
   Force can be referenced to the object such as force associated with distorting the surface (spring forces are of this type) or to any other position coordinate

2. Forces that are proportional to rate of movement (velocity):
   Friction and viscous forces are of this type. The force in a shock absorber is of this type

3. Forces that are proportional the rate of change of speed (acceleration):
   These are inertial forces related to accelerating or decelerating a mass.

Let us imagine how a linear shaft driver could simulate an arbitrary force. The first task is to control the reaction force with no movement. We can define the actuator force, Fl to be equal to a test force F2 if the following conditions are met by the actuator:

a. When Fl is less than F2, the actuator, moves in the direction of F2.
b. When Fl is greater than Fl, the actuator moves in the direction of Fl.
c. Then when the actuator does not move, F1 is equal to F2.

This can be accomplished by constructing a linear motor that can be moved in steps in the direction x for a period of time and then allowed to be pushed in the direction -x a distance that is proportional to the applied force F2. The result will be a mot ion (mx - nx) that is proportional to the applied force.

By controlling the duty cycle of the process (the ratio of the time that the shaft is driven in the x direction to the time that is allowed to slip in the -x direction) the two motions can be made equal and opposite. Therefor the shaft will behave as thou gh it were supported by a force Fl equal to F2. From this we see that we can simulate any force within the range of the motor. If we input time and shaft position we can program to produce

(force as a function of position (spring)
(force as a function of velocity (friction)
(force as a function of acceleration (Mass)

Therefore a stepped linear drive with a controlled slip friction can be programmed and controlled to simulate an arbitrary general force.

Task 3.3 Concept Selection

Will select those actuators that will be perfected and tested. The selection(s) will be made in conformation to the requirements of Task I with consideration for the products that have the best prospect for Phase II commercialization.

TASK 3.4 PROTOTYPE DESIGN

Will complete the design and engineering of the specific devices selected in Task 3.3. This will require mechanical design, magnetic circuit design, design of the drive electronics and control software. Each of these tasks will be directed to optimizing the specific performance of the device, i.e. reducing the size, weight, power requirement and increasing the band width and dynamic range of the device(s).

TASK 3.5 PROTOTYPE CONSTRUCTION

Prototype construction will be done in-house with the possible exception of a few high precision parts. The TRA machine shop is currently capable of performing most prototype work. If special machine work is required it will be purchased locally.

This task includes fabrication of the mechanical device, assembly of the drive electronics and development of control software. The robotics applications envisioned at this time will likely have a computer interface between the Master and Slave in order to track and translate commands and sensor feedback so it makes sense to put as much control logic as possible in the same computer.

TASK 3.6 TEST/MODIFY

The actuators will be functionally tested to see if they meet the design specifications. We anticipate that there will be some iteration of tasks 3.6,3.4 and 3.5 as the prototype is modified to improve its performance.

TASK 3.7 DOCUMENTATION

Test data will be analyzed and documented during this task. Device design documentation will be corrected to include any modifications made as a result the optimization process.

TASK 4. APPLICATION SIMULATION

It is beyond the scope of this project to produce a complete commercial robotics system. However, it will be necessary to accurately characterize the actuators in as close to real application conditions as is possible within time and budget constraints. We will approach this two ways. We will create a PC based virtual reality controller that is capable of supplying signals to the actuators that simulate those that could be expected from real transducers. The computer will be capable of producing simulations of a wide range of virtual conditions. The other approach will be to construct test fixtures that represent a useful range of real application conditions. A major portion of this task will necessarily be devoted to the creation of the simulation instrumentation and fixtures. The remainder will be in providing test feedback for actuator design refinement and optimization.

TASK 4.1 VIRTUAL FEEDBACK SIMULATOR

The basic purpose of the simulation software development is to provide a virtual test bed to simulate slave robotic environments. It is of secondary concern to the actual function of the actuator development however, it is necessary for testing the proposed devices. It is envisioned that the software will be formulated in such a way as to allow testing of individual actuators, joints or motors, and later in the project for testing of actuators integrated into a dexterous exoskeleton test bed. The virtual objects created in software will test the limits of device actuation. The objects will be made to simulate, hard and soft objects, moving objects, active spring type objects, textures, and vibrating objects. Since software control signals are well defined this will provide a direct comparison of actuator input versus output of an instrumented actuator. The software developed in this portion of the project could provide the foundation for spin off virtual reality systems integrated with dexterous feedback. The system will be designed to operate using control parameters to be defined and specified in Task 1.

TASK 4.2 MECHANICAL SIMULATION

One of the difficulties of the software simulation is that it is difficult to predict, a-priori behavior of real robotics devices. To solve this problem, simple mechanical slave robot actuators will be developed. These simple slave actuators will be instrumented to measure force and position. The slave actuators will allow grasping and clamping. This will allow placement and manipulation of know objects with various characteristic and provide direct comparison to forces sensed by human manipulation directly or through a given actuator interface.

TASK 4.3 FORCE FEEDBACK MASTER

The ultimate goal of this project is to develop new actuators which could enhance the performance of dexterous exoskeletons through the use of high performance force feedback. For this reason it will be an objective of the project to integrate the developed actuators, both resistive and active, into a prototype dexterous exoskeleton test bed or master. The device will be formulated in accordance with the design specification developed in Task 1 of the project. And will be interfaced to the virtual simulation environment noted above. The master device will be formulated with sufficient complexity to full demonstrate the potential of the new actuators and provide for conceptual demonstration important for technology transfer to Phase III commercial concerns and applications.

TASK 5. Documentation

Project documentation will be done with an anticipation of Phase III commercialization. Attention will be paid to as- built device documentation, and performance specifications. Documentation will also include analysis of application suitability and scale ability of the actuator technology. A careful study will be made of test data and results. A final report along with a review of progress through the project will be provided. The final report will recommend devices and applications for Phase I II commercialization.

RELATED WORK

TRA has just completed the Phase I “proof of concept” project New actuators for Human Sensory Feedback . The following results are directly related to the present proposal and are excerpted from the Phase I final report:

LITERATURE REVIEW

The project began with a review and study of existing knowledge regarding robotic dexterous telemanipulation and magnetostrictive technologies. A bibliography is attached at the end of this report. The study confirmed the need for new actuators which can be integrated into new exoskeleton hands to facilitate force feedback with the needed response characteristics and brought the research team up to speed on state of the art devices, methods and ideal sensory specifications. In addition to a general literature review of telerobotics and dexterous feedback a specific review of relevant information on Terfenol-D magnetostrictive material and its current applications and theoretical design considerations was begun. This information will be useful in future design of actuators.

The use of the Terfenol-D material for mechanical actuators is a relatively new concern and the literature is some what limited. It has been primarily studied for use in sonar and vibration control applications. Non the less, significant effort is being expended by various researchers in bringing the use of the Terfenol-D magnetostrictive material to a commercially viable state for various applications including: vibration control, rotary motors, speakers, hydraulic pumps, brakes, linear motors, magnetic field detectors and sonar. A list of relevant literature is included with this document.

RESISTIVE ACTUATORS - CONCEPT DEVELOPMENT.

Actuator concepts presented in the Phase I proposal, in schematic form, were developed to reevaluate their applicability to the task at hand. In the proposal it was believed that a useful way to develop the new actuators was to modularize the function into resistive components and active components (see Phase I proposal). By resistive we mean brake type actuators which would resist the forces exerted by the hand. The active devices would provide both force and be position driven. The ideas presented in the original proposal were evaluated and studied as they might be formalized in physical form. We began with simplified geometry's to provide "sanity checks" and establish feasibility of braking methods early in the project. The ball type brakes (see Figures 1,2) are relatively easy to fabricate and were the first tested. Crude prototypes were fabricated using standard 60601-T6 aluminum and standard size rods of Terfenol with .2 inch diameter and 1 inch in length (Etrema). The early discovery designs were exploratory in nature and were not refined. The aluminum housing had relatively coarse threads and fine adjustment of prestress was difficult to establish and maintain. Since the Terfenol rod provides extremely fine motions, fine adjustment was difficult to maintain on these early discovery prototypes. The prototypes functioned well considering the fact that they were not optimized.

At this stage of the project several possible products were envisioned which could utilize the mechanically simple design concepts of the ball joint resistive actuators. TRA is currently exploring commercial possibilities for off shoot products related to these early discovery experiments.

Since the output force of this simple device was not close to the theoretical maximum which the Terfenol can produce second generation devices were designed and fabricated to investigate the measurable effects on output force of material stiffness and friction. Second generation actuator housings were produced in order to evaluate the effects of compliance and hardness on the braking of the actuators while more sophisticated models of the Terfenol strain and the magnetic circuits could be developed. Figures 3 & 4 illustrate the second generation devices. The devices were tested using an Einstein Universal testing machine. The actuators were placed in a horizontal position and the cross head was driven at various speeds (see Figure 5 for experimental setup). The load cell measured the magnitude of the force to move the joint at a constant speed. Due to the setup configuration, the lever arm length changes slightly as the angle of the joint varies. To minimize this variation comparisons are made close to the horizontal position.

The actuator configurations tested at this early stage in the project functioned well even though magnetic fields and magnetic circuit design was not a priority. Various materials were used as the frictional ball members (stainless steel, chrome steel, aluminum, plastic). The maximum braking forces obtained with this configuration were more a function of material stiffness than the actual coefficient of friction of the material. This is likely due to the fact that the strain of the Terfenol is small and the more compliant frictional members deform away from such small motions. The ideal material will posses both a high stiffness (similar to that of Terfenol) and a high coefficient of friction.

The testing at this stage of the project also confirmed that the brakes could be made to brake with a force proportional to the driving voltage (current). This is important from the standpoint of eventual proportional control of the actuators.

The following graph (Figure 6) is illustrative of the test data gathered. Note that the force is controllable and proportional to voltage. The maximum forces were obtained when the maximum prestress was placed on the Terfenol by means of the adjustment threads. This is consistent with results from other Terfenol-D researchers. Figure 7 converts the raw data to Newtons and relates it to the applied field. It is both a reflection of the characteristics of the Terfenol and the stiffness and mechanical slop of the actuator housing.

In testing the early devices it became clear that there are several practical considerations that needed to be evaluated to produce a physical useful device. A third generation resistive actuator was developed to address some of the more obvious design limitations and to begin integration with a rudimentary two digit exoskeleton. The following discussion summarizes some of the design criteria which was collected and evaluated for application and design purposes.

Terfenol-D is an alloy of terbium, dysprosium and iron. It is a giant magnetostrictive material. As such when the substance is in the presence of a magnetic field the material undergoes a strain. Terfenol crystal has a direction of maximum magnetostriction which is in the [33] crystallographic direction. Here strain is defined as (l/l where l is the length of the Terfenol.

Figure 8 is a plot of strain (S) versus magnetic field (H) for ETREMA [1] Terfenol-D. S can be seen to not only depend on the magnetic field, but also on the mechanical prestress (T) where stress is defined as force per unit area. Terfenol-D has a point of maximum strain or saturation and also sufferers from hysteresis. If the operation of the Terfenol is constrained to operate out of the region of saturation and the hysteresis is ignored a magnetostriction constant (d) can be defined which is the slope of the curve. With this linear approximation several fundamental equations [1]can be defined:

$S=sHT+dH$ 1

$B=dT+mTH$ (2)

where sH is the inverse of the modulus of elasticity at constant magnetic field and (T is the permeability at constant stress. The following is a table of nominal properties of ETREMA Terfenol-D [1].

In the design of actuators two extremes can be envisioned. First, actuators with translational motion and low force. Second, those with force and low translational motion. In the second case equation one can be rewritten as,

$F=(S-dH)sHAC$ (3)

where AC is the cross-sectional area of the Terfenol-D material. As can be seen from this equation the strain is an impedance to the force output and must be minimized. However, an application of a prestress creates a negative strain in the material and can be used to delete the effects of the strain or to enhance the force output of the actuator. As to the first case equation one can be rewritten as,

$Dl=(sHT+dH)l$ (4)

where l is the length of the Terfenol-D rod. Equation four shows that application of a prestress enhances the maximum motion of the actuator.

COILS

For actuators the most convenient method of generating a magnetic field is a solenoid. For an ideal solenoid the magnetic field is

$$H= N/L \times I \quad (5)$$

where L is the length of the coil, N is the number of turns and I is the current through the coil. N/L can also be defined as n the turns density. Thus, there is a trade off between the current and the turns density. As the turns density increases, for a fixed coil length, the number of turns increases and the number of coil layers increases. The outer solenoid layers become weekly coupled to the Terfenol-D and the coil becomes less efficient. Because of this week coupling of the outer solenoid layers, there is an inverse relationship between turns density and electrical efficiency. Figure 9 is a plot of coil wire diameter versus electrical power for a fixed magnetic field of 650 Oe and an inside diameter of 0.2 inches and an outside diameter of 0.4X inches and a length of 1.0 inch. The discontinuities of the line are due to wire packing. That is there is a fixed set of wire diameters that will fit or fill the allowed solenoid length.

MAGNETIC CIRCUIT

If the solenoid length is much greater than its diameter then the B in the Terfenol-D is uniform and the fringing effects of the ends can be ignored. Or another way of stating this is that the solenoid ideal equation will hold. Another way of approaching this problem is in providing a magnetic return path. The magneto motive force is the electrical analog of voltage and is

$$mmf=fA \quad (6)$$

where (D is the magnetic flux or the dot product of B and AC and 93 is the reluctance. The flux is the analog of electrical current and reluctance is the analog of electrical resistance. Thus the reluctance defines the flux in a magnetic circuit. (is defined as,

$$A=L/Acm \quad (7)$$

where L is the path length, Ac is the cross-sectional length and it is the relative permeability. For an actuator the mmf is provided by a solenoid and is NI, where N is the number of turns and I is the current through the coil. As in a series electrical circuit where the current is a constant, in a series magnetic circuit the flux is a constant. Thus if a magnetic return path is provided with a reluctance much less than Terfenol-D the reluctance of the return path can be ignored. This can be accomplished by providing a return path through a ferromagnetic material with a permeability much greater than that of Terfenol-D. In this case the solenoid ideal equation holds.

Figures 10 - 13 illustrate the final resistive brake actuators developed under this Phase I project. The devices are not ideal by any means but they were designed with consideration of the ideal equations above. Because of limited resources of the Phase I (time & money) exotic materials and geometries were not available and therefore ideal conditions were not achieve. This means that significant improvements are very achievable. In a

Phase II more refined actuator designs will be developed.

Figures 10 & 11 show the ball joint actuator. Figures 12 & 13 show the one axis brake. It was decided to integrate both of these actuators into a demonstration exoskeleton.

EXOSKELETON

The ball joint actuator gives significant degrees of freedom. The single axis joint demonstrates a simple brake actuator. The Phase I exoskeleton is by no means ideal but serves as a test bed for the actuators and illustrates one possible application for these devices. The exoskeleton development assisted the researchers in developing a better understanding of practical issues facing mounting and interfacing with the human hand. In Phase II more anthropomorphic designs will be achieved as the size and efficacy of the new actuators are improved. It is believed that for most robotic applications that a simple resistive feedback system would provide the human operator significant and intuitively useful forces without the cost and complexity of a fully active exoskeleton. In Phase II we plan to continue development of both the resistive and linear motor configurations. It is likely that the most versatile systems may be hybrid systems in which assorted actuators are specified depending on the complexity of the robot slave.

Figures 14 & 15 show the demonstration exoskeleton fitted with resistive joints. It consists of one ball joint actuator and one single axis joint actuator for each digit. The apparatus is fitted with a standard glove. Providing positional feedback to the hand was not within the scope of the Phase I but one can see that the actuators could easily be integrated with sensors such as in the DataGlove(TM).

The four solenoids constructed for the resistive braking components were constructed out of 30 AWG wire. They have 750 turns of wire. These coils are designed to produce a magnetic field of 650 Oe at a current of 2 amperes. This does not excite the maximum output capability of the Terfenol but operation in the more linear portion of the curve. The coils have a outer diameter of 10.4mm (0.41 inches), an inner diameter of 5.2mm (0.205 inches) and a length of 27.9mm (1.1 inches). They were designed to energize a 26 mm (1.03 inch) long by 5.1 mm (0.2 inch diameter) Terfenol-D rod.

At this field strength the Terfenol rod will produce a maximum clamping force of 457 Newtons (102 lbs) or a maximum extension of .02 mm (800 microns).

Because of non ideal (low) coefficient of friction of the ball materials available in Phase I and the compliance of the overall structure, the actual output of these prototype devices is significantly less than the design force. (see above instron data). In the ball type actuator we used chrome steel ball bearings. These have a low coefficient of friction which is not really appropriate for the actuator but still illustrate the function and design concepts. The actuator housing is made of an air hardenable tool steel. This improves the magnetic circuit significantly compared to the aluminum and stainless steel of the early prototypes but is by no means ideal.

In the one axis joints we use a ground tool steel shaft. A higher force is obtained in the one axis joint compared to the ball joint because the coefficient of friction of the axle is higher than the chrome steel ball.

The coils are not ideal because of fabrication limitations. The coils were hand wound and are not at the ideal packing ratios. Automated winders can improve this. In addition the coils are free floating inside the actuator housing. This detrimentally affects the heat flow out of the coil and actuator. In Phase II devices the coils should be potted in place with, thermally conductive epoxies or greases to improve heat flow and reduce failure due to wear. An additional negative side affect of the lose coils is that the coil tends to bounce inside the housing when power is applied. Since the Terfenol is already pre stressed in the actuator the device would essential be silent when power is applied if the coils were rigidly potted inside the housing.

MAGNETIC CIRCUIT

The mmf for the actuators is supplied by the solenoids. The magnetic return path consists of pole caps which extend into the solenoid and the steel solenoid housing. These details can be seen in the mechanical drawings of the actuators (see above figures).

ELECTRONICS

Figure 16 is a schematic of one of the four actuator energizing circuits used to drive the demonstration resistive actuators. The Omega PXI60-030GV pressure transducer, which is labeled JP2 PX160, converts the pressure from the pressure bulbs, (see demo schematic) in Figure 17 & 18, to an electrical differential voltage which is amplified by an instrumentation amplifier and placed across the actuator. The darlington transistor, Ql, supplies the current to the actuators.

LINEAR MOTOR ACTUATORS - CONCEPT DEVELOPMENT

Along with the study of the resistive brake type actuators it was the goal of the Phase I project to begin research into the development of Terfenol-D driven motors. Concepts for piezoelectric, and magnetostrictive motors have been given some attention by other researchers. The linear motors are often referred to as inch worm devices because of the mode of movement. The devices are, in general, conceptually simple but require careful design to bring the concepts to fruition. The devices function by re petitive clamping, expanding and clamping. The devices will allow very precision microsteps and are ideally matched with digital control. The inch worm devices require phased driving of actuators. In principal the devices can be very fast relative to t he speed of human hands and could provide large forces.

TRA began the study of linear Terfenol motors by duplication of the concepts thought in several patents (see bibliography). A prototype of the device was designed based on available information and tested (see Figures 19,20). The devices as described in the literature were marginal and careful study reveals several practical limitations of the linear motors. One primary limitation of the concepts in which the Terfenol rod inches its way through a hollow tube is t hat the change in diameter is small compared to the change in length. Very high precision is required to achieve motion. The overall travel is also limited by the precision to which the hollow tube can be formed. Long, hollow precision tubes are difficult to make. New patented ideas suggest using spring loaded plates to entrap the Terfenol. These concepts are limited because the forces varied as Terfenol-rod moves relative to the tension springs. An additional undesirable restriction is incurred by the fact that the driving coils are placed outside the friction plates. In such designs the volume efficiency of the magnetic circuit is lowered. In these designs, as a practical matter, the Terfenol rods function directly as the friction surfaces and holding a tolerance for extended runs would be difficult because of wear. And finally the motors provide only a predefined output force dependent on the faction of the mechanical strings. After studying these obstacles and other related technologies it was decided to develop a linear motor which draws on the methods developed for both rotary Terfenol motors and piezo inch worm linear motors. In these devices individual elements are separated. The devices function by clamping a structural element with one actuator, expanding a second element to inch forward and a third element of clamp- at the new position. The sequence is then repeated. The kind of design is particularly interesting for the Terfenol motor for several reasons. First, the clamping fun ctions and push function use the full potential of the magne tostrictive motion which is an order of magnitude higher than piezoceramics. Second, the actual wear surfaces need not be Terfenol. Third the driving coils can be intimately fitted on the Terfe nol rod for minimum volume packing. Fourth the driven element can be long, such as a standard metal shaft. Fifth, fabrication tolerances can be reduced by providing adjustment means as demonstrated on the resistive elements. Sixth, the devices can be configured as either normally locked or normally free. And finally the designs facilitate the development of a variable resistance or force motors in which the clamping forces can be actively controlled by variable voltage input to the two clamping coils.

Figures 21, 22 & 23 illustrate the motor design chosen. The size of the Terfenol-D rods around which the motor was designed were arbitrary. The overall size of the prototype is not indicative of any final size for the application of interest to this proposal. The TRA motor consists, essential of two symmetric halves, three Terfenol rods, three separately driven coils, retention springs and a output shaft. In this particular device the maximum velocity of the de vice is determined by the spring stiffness and the mass of the two housing pieces. In the next generation of the device TRA has devised a method which eliminates the need for the springs and reduces the main housing from two to one piece. The device for demonstration purposes is driven using a fixed logic phasing circuit. The driving circuit could be greatly improved with variable duty cycles and optimized pulse widths and using programmable logic. The precision of the prototype is low. The function c an be improved greatly, but it illustrates a powerful concept.

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Relationship with Future Research or Research and Development

The proposed Phase II project is to provide an advanced development of new magnetostrictive actuators for specific application to telerobotic systems. The project will develop modular actuators for both proportional braking and linear motion. As demonst rated in Phase I the concepts are feasible but need significant refinement and optimization to bring them to a commercially usable state. When brought to this state at the end of Phase II the actuators will find wide use in robotics for both dexterous exoskeleton masters and slave robot end effectors. The devices could also have significant application for systems where active, rapid response, high force actuators are needed such as vibration control, vibration isolation and various commercial automation systems- At the conclusion of Phase II the actuators will be well characterized and be directly implementable in sophisticated robotic systems. The information formulated during Phase II will allow transfer of technology to other Air Force and military entities and to the commercial market. In Phase III, TRA plans to market individual actuator modules, exoskeleton controls and virtual reality force feed back systems. The Phase II advanced development is crucial to achievement of such commercialization goals. The technical obstacles to be crossed in order to bring the new technology to Phase III commercialization are significant the feasibility demonstrated in Phase I and the program outlined in this Phase II proposal will lay a solid foundation for successful commercialization. The availability of the new highly responsive new magnetostrictive brakes and motors should be well received for many specialized robotic and automation applications.

Commercialization Strategy

Small, light weight, fast, high force, feedback controllable actuators could find wide application by both military and commercial entities for telerobotics applications. The completed devices could also be used as actuators in a great number of automated mechanical systems found in office, home and factory environments. Products could include: actuators, simulation software, compact brakes, active vibration control modules, tactile devices, robotics controls, digitally controllable springs, active exoskeletons, linear motors, digitally controlled clutches and dash pots etc.

Key Personnel

The technical personnel at TRA form an innovative team with broad scientific and engineering backgrounds. The interchange of ideas necessary for problem solving occurs frequently and spontaneously. The personnel for this project are well suited to develop the new actuators using smart materials and to cope with problems that may arise during the project.

Owen D. Brimhall, is a principal investigator and manager of the Bioengineering Division at TRA. He is currently a principal investigator for the National Science Foundation, National Institutes of Health, and the U.S. Army. Mr. Brimhall is a senior research engineer with a degree in mechanical engineering and leads the product development group at TRA. He has done extensive work at TRA on innovative technologies and medical devices. Three of these technologies, developed with the assistance of the SBIR program, have been licensed by Phase III companies for commercialization. Mr. Brimhall has broad experience with the study, design, testing, and evaluation of prototype and production devices. As a researcher Mr. Brimhall has been closely involved in a number of research contracts including Sensory FeedbNew Actuators for Human ack (DOD-Phase I), The PI’s broad background in engineering and management qualifies him to direct this study.

H.R Curtin, Ph.D., is a Senior Scientist at TRA with extensive experience in the development of new technologies. He has a physics background and is an expert at biofeedback instrumentation. His expertise will be used to aid in modeling and design of the new magnetostrictive actuators and in system integration the anthropomorphic exoskeleton dexterous masters and feedback actuator control.

Dan Knowlton, is a research scientist at TRA, he is currently developing and testing mathematical models of new Terfenol-D magnetostrictive resistive joint actuators to optimized power and size for a robotic exoskeletal feedback. He will aid in actuator design and testing.

Charles Galway, is a bioengineer at TRA, he will aid in concept definition, fabrication and testing of the prototype actuators.

BRIEF RESUMES OF THE KEY PERSONNEL FOR THE PROPOSED PHASE I PROJECT FOLLOW THIS SECTION:

BRIMHALL, Owen D. Senior Research Engineer

Education

University of Utah, 1983 Graduate studies

Brigham Young University, 1981-82 B.S. Mechanical Engineering

University of Utah, 1977,1980 Engineering

Employment

1989-present Manager, Bioengineering Division-Principal Investigator (PI)

Technical Research Associates

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Direct the study of innovative technologies, research, product development. PI on the following projects:

Utrasonic Field-Flow Fractionation (NSF-Phase I) Acoustic Velocity Gradient Fractionation (NIH-Phase II), Advanced Development/ruggedization of a Multipurpose Centrifuge (U.S. Army-Phase II), New Actuators for Human Sensory Feedback (U.S. Air Force-Phase I), Disposable Plasmapheresis Device (NIH-Phase I), Ultrasound Enhanced Inverted Bone Marrow Fractionation (NIH-Phase I), Multipurpose Centrifuge Dev. (U.S. Army).

1987-89 Senior Engineer - Product Development Group Leader

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Research, product research, proposal writing, development and design. Products developed include:

HemataSTAT (tm), AccuCRIT (tm), Urinary Continence Device, Ultrasonic Hematocrit, ELF-monitor(tm).

1984-87 Research Engineer

Technical Research Associates

Duties: The conception, study, design, evaluation and testing of prototype devices. Proposal writing. Projects included Ultrasonic Cell Sorting devices, Centrifugation Devices, Artificial Sphincter, Urinary Bladder Continence Device, Ultrasonic Aqueous Humor Clarifier, Microanastomosis procedure, Extrapulmonary Blood Exchange Device, Ultrasonic Blood Cell Separator, Rapid Hematocrit Devices, Material Process Procedure for Bone Cement.

1983* Electronic Technician

Chemistry Dept., University of Utah

1979-82* Commercial Artist, Draftsman

G.C Advertising Dept., SLC, UT

Edwards & Daniels Architects, SLC, UT

Big Horn Oil Co., SLC, UT

Patents:

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5,139,328 1992 Noncontact Hematocrit Reader Apparatus and Method

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Brimhall, O. D., Ultrasound Enhanced Inverted Bone Marrow Fractionation, Final Report, 1991 NIH SBIR Phase I Grant, R43-HL45410-01.

Brimhall, O. D., Development of a Multipurpose Centrifuge, Final Report, 1991 U.S. Army M.R.D.C., Contract No. DAMD 17-91-C-1020.

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Curtin, Howard R.

Senior Scientist Education Brigham Young University 1967-1991 Ph.D.

Physics Brigham Young University 1959-1964 B.S., M.S. Physics

Professional Experience

1992-present Senior Scientist, TechnicalResearch Associates, S.L.C. , Ut. Conduct research and product development related to biomedical instrumentation and devices.

1991-1992 Consultant, Self Employed Physics and Technology related consulting, Clients included: Med Tech inc., BioArc inc. , Logis inc. Ashurst Technology

1984-1989 President, Consolidated Research and Technologies Inc. Development and clinical investigation of computer based biofeedback instrumentation, consultant to clinical research program to determine the clinical efficacy of low power laser therapy, development of process controller for large scale medical oxyge n concentrator.

Other proprietary research and development projects:

1976-1984 Senior Scientist, Manager Advanced Systems Department, Eyring Research Institute Projects included work in high energy plasma phenomena, Solid state Beta battery development, theoretical and experimental work in advanced electromagnetic. invention and product development of a new class of radio military antennas.

1981-1984 Partner, Radiation Physics Consultants Provided consulting services in Medical and radiation Physics to several Hospitals and clinics

1973-1976 Director of Utah State Information Systems Center State of Utah Directed the Information systems development and data processing for all agencies of state government

1973-1973 Acting Director of Computer Services Rochester Institute of Technology Faculty and administrative position

1971-1972 Associate Professor of Radiology University of Utah School of Medicine Supplied clinical support and conducted research in diagnostic ultrasound. Established research program in real time ultrasonic holography, using techniques and equipment d developed while at Battelle Northwest Laboratorie

1964-1967 Scientist, Battelle Northwest Laboratories Reactor Computer simulation,; Nondestructive testing engineering,(worked with ultrasound, eddy currents , x-rays, and optical emissions as non destructive testing tools); Solid-state physic and optics. (laser research included phonon-photon interaction in semiconductors, laser tracking of atmospheric gases in the atmosphere and methods making ultrasonic images visible) Principal investigator on a project to investigate new R.F. propagation modes in the Earth and in Sea Water.

Selected Reports and Publications

“Effect of Pressure on the Intermetallic Diffusion of Silver in Lead” H.R. Curtin, D.L. Decker, and H.B. Vanfleet, Physical Review 139 (8/30/65)

“Ultrasonic Amplification in Cadmium Selenide” R.L. Gordon, V.I. Neeley and H.R. Curtin, Proceedings IEEE, Vol. 54, No. 12

“Effect of Pressure on the Interstitial diffusion of Lithium in Germanium to 45 Kbar” H.B. Vanfleet, D.L. Decker and H.R. Curtin, Physical Review B. Vol. 5 No. 12

“Medical Imaging Capability of Liquid Surface Ultrasonic Holography” H.R. Curtin and R.S. Anderson, paper presented at the S.P.I.E. Application of Optical Instrumentation in Medicine, Chicago, 1972.

“Analytical Investigation of the Transient Electrical Behavior of Water” H.R. Curtin, ERII #700-0006 (5/18/79)

“Measurement of the Effects of Radiation on Parameters Affecting Leakage in Integrated Circuits: R. Woodbury, H. Fletcher, and H.R. Curtin, ERII #D101

“Long Range Strategic Communications System Using Ground Wave Propagation” R.Losee and H.R. Curtin ERII #D-105

Numerous Lectures at Medical and Consumer Health Conferences (1984 to present)

Knowlton, Daniel D. Research Scientist

Education

University Of Utah,1992 MS Physics

University Of Utah,1989 BS Physics

Employment

1992-Present Associate Researcher Technical Research Associates 2257 South 11 East, SLC, UT

Duties: Research new technologies, modeling, experimental design and testing. Projects have included the study of Magnetostrictive actuators, circuit design, mathematical modeling, exoskeletal feed back devices, ultrasonic particle separation methods, ELF measuring devices.

1990 Research Scientist Future Research, SLC, UT

Duties: Design, construction and testing the electronics for low level x-ray radiation detectors used in state of the art concealed weapon detection systems.

1989 Laboratory Assistant Crystal Growth Laboratory Physics Dept., University of Utah, SLC, UT

Duties: Prepared materials for and grew crystals. Crystal growth techniques included: Czochralski and Bridgeman. Operated and maintained high vacuum systems. Glass blowing, metal and wood machine tool operator.

Experience

Computer languages and operating systems: C, 8OX86 assembly, Basic, Unix, MS DOS systems. Analog and digital electronics design and signal processing.

Galway, Charles R. Bioengineer

Education:

University Of Utah, 1990 B.S. Biology University Of Utah, 1974-81 Mechanical Engineering

Experience:

1984-Present Bioengineer Technical Research Associates 2257 South 1100 East, SLC, UT

Duties: Research, design, fabrication and testing of innovative technologies. Projects include; isothermal foot apparatus, ultrasonic plankton analysis, artificial sphincter apparatus and bioreactor apparatus.

1983-84 Research Technician Utah Biomedical Test Laboratory, SLC, UT

1982-83 Computer Repair Technician Quality Technology, SLC, UT

1978-82 Machine Shop Technician Utah Biomedical Test Lab, SLC, UT

1974-75 Technician Field-Flow Fractionation Laboratory Chemistry Department, University Of Utah, SLC, UT

Selected Reports and Publications

Baker, C. D., Galway, C. R., (1991) “Computer Controlled Thermal Foot”, Final Report U.S. Navy Contract N00140-91-C-2655

Baker, C. D., Young, J. D., Galway, C. R. (1981) “Evaluation of the Deseret Company Angiocath Cannula”, UBTL in House Report

Schoenberg, A. A., Sullivan, D. M., Baker, C. D., Booth, H. E., Galway, C. R., (1982) “Ultrasonic PVF2 Transducers for Sensing Tactile Forces”, UBTL in House Report

Patents:

4,705,518 November10, 1987: “Artificial Sphincter Apparatus and Method” (Applied) “Bioreactor Apparatus And Method”

FACILITIES/EQUIPMENT

From its beginning in 1983, TRA has developed into a multi disciplined research, development and manufacturing enterprise. TRA has been successful at developing technologies and transferring them to commercial markets and Phase III companies. TRA has sold several technology license agreements to companies including: Toyobo, Japan; Alcan, Canada; Baxter, USA; STI, USA and others. TRA continues to expand in R&D, engineering, manufacturing and product sales. TRA has both active R&D and light manufacturing facilities on site.

TRA is a research and development company with manufacturing capabilities. It has developed expertise and products in several cutting edge technologies: bioengineering, materials science, biotechnology, electronics and product design. The P.I., Owen D. Brimhall, has accumulated substantial experience with the development of novel mechanical and electromechanical systems for application in engineering, bioengineering and medical technologies. He has worked on both surgically implanted and non invasive devices as well as laboratory instrumentation.

The principal investigator is currently investigating Terfenol-D as it may apply to dexterous exoskeleton controls in a Phase I project for the Air Force. The PI. is also conducting research under a NIH grant on the study of Acoustic Velocity Gradient Fractionation for separation of bone marrow and other cells and developing a state of the art, light weight, small ruggedized multipurpose centrifuge for the Army. The centrifuge integrates the functions of fecal concentration, urine sediment, quantitative buffy coat analysis, micro hematocrit measurement and blood sedimentation into a single small unit with a built in electronic controls and an electronic procedural manual which prompts the operator through the various tests. In addition TRA has successfully developed several commercial instruments including the HemataSTATTM manufactured by STI (Separation Technologies Inc.), ELF-monitorTM (TRA).

2. MAJOR EQUIPMENT/ ADDITIONAL INFORMATION:

TRA has all the major equipment required for this project. TRA has complete managerial, laboratory, electronic and machine shop facilities. Equipment includes Instron universal testing machine, chart recorders, computers, oscilloscopes, signal gene rators, microscopes, machine tools, etc.

CONSULTANTS

No consultants are currently enlisted. TRA however, will use expert consultants as necessary in order to assure the success of the project.

CURRENT AND PENDING SUPPORT

RA has no prior, current or pending support for a similar project