Remote Planetary MEchanical MIrroring using Controlled stiffness and Actuators (MEMICA)

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1.0 OBJECTIVE

The Rutgers University/JPL team is proposing to develop a haptic system, so-called Remote MEchanical MIrroring using Controlled stiffness and Actuators (MEMICA) to support human operation in space augmenting astronauts' activity, providing countermeasure to zero-gravity, establishing medical training as well as addressing other critical needs. The key element of MEMICA is a novel miniature, lightweight actuator that will be developed and integrated into a glove for demonstration of the technology at TRL 3. The team will design, fabricate and test this novel actuator that will be able to apply large density forces and achieve large displacements using a compact mechanism. The proposed ECFS (Electrically Controlled Force and Stiffness) actuator is based on a hybrid combination of Electro-Rheological Fluids (ERF) and electromagnetic actuation concepts. This new class of actuators is expected to have capabilities superior to conventional electromagnetic, hydraulic and pneumatic-based actuation systems. It will have unique advantage of being able to accurately control not only the developed forces but also its compliance and damping. Moreover, in its inactive mode the actuator does not produce counter forces and thus the user can disable their operation allowing them to be "out of the way" until needed. We will design and fabricate compact prismatic joints mobilized by ECFS actuators. We will perform tests to demonstrate the effectiveness of the ECFS actuators to power joints of force-feedback devices and haptic interfaces. Further, a glove will be constructed to demonstrate the operation the ECFS actuators at the level of a hand.

2.0 EXPECTED PLANETARY APPLICATIONS FOR MEMICA

The developed technology will address the following applications/issues:

- EVA – Increasingly astronauts are required to operate outside the Space Shuttle or the Space Station. These EVA tasks are tedious, particularly when conducting delicate operations, due to the significant forces operating on the suit resulting from the pressure difference between the suit and the ambient high vacuum environment. MEMICA would offer the ability to produce a powered suit that amplifies the physical activity of the astronauts and making their activity less strenuous.
- Zero Gravity Countermeasures – Extended human operation in space involves loss of muscles and bones. To minimize this space effect an exoskeleton suit can be designed that allows astronauts to experience reaction forces at the level and orientation as would be expected on earth.
- Remote operation of Robonaut – The JSC's Robonaut is designed for telepresence control and it is intended to support remote tasks where it is operated as a surrogate robot. It is able to maneuver through areas too small for the current Space Station robots. The Robonaut is designed as an anthropomorphic robot, similar in size to a suited EVA astronaut and it is mounted on a robotic arm that is capable of dexterous, human-like maneuvers to ensure safety and mission success. Robonaut was designed so that a human operator who is wearing suit/gloves with sensors can control it. Unfortunately, due to unavailability of force and tactile feedback capability, the operator determines the required action by visual feedback, i.e. looking at the Robonaut action at the remote site. This approach is ineffective and consequently limits the potential tasks that Robonaut can perform. MEMICA offers the necessary haptic interface to allow the operator to "feel" the mechanical conditions at the Robonaut site.
- Training - The ability to simulate an operation using virtual reality is critical to many technology areas. It allows training operators in hazardous and risky tasks as well as developing procedures that emulate reality. MEMICA would add a very important tool to the capability to train astronauts in simulated environments where they can "feel" the actual environment and thus have more realistic simulation and effective training.

- Simulated medical procedures and guided medical operations – The capability to train medical staff or to remotely guide the operation of the staff is a critical capability that can benefit sites that are lacking local medical-care facilities or specialized medical staff. Besides helping rural areas and the military in battlefields, "telesurgery" can benefit future NASA missions. Manned missions are being pushed to new frontiers, at growing distance from earth and are expected to last years. A major obstacle may rise as a result of the unavailability of on-board experienced medical staff. The use of MEMICA will allow mission personnel to practice required urgent care procedures, while being remotely guided and using all-in-one type surgical tools to perform the needed procedures. The specific procedures will be updated by downloading the latest software onboard the spacecraft's simulation system.

The developed technology is expected to have many spin-offs to terrestrial applications including medical, military, sport, training, entertainment, etc.

3.0 BACKGROUND

Human operated missions are progressively being extended in terms of duration and distance from Earth at a growing complexity and thus increasing the challenges to the accomplishment of the tasks and the assurance of the astronauts' health. Some of the issues include (a) Conducting delicate EVA task is time consuming and tedious task that requires effective powered-suit; and (b) Low gravity causes bone and muscle deterioration loss and the damage increases with time [Long, 2001]. With the increase in mission duration it would become highly probable that a medical emergency would occur necessitating a treatment that requires expertise beyond the capability of the on-board crew.

Members of the proposing team conceived the haptic MEMICA system in order to address these challenges to space exploration [Bar-Cohen, et al, 2000]. This system potentially provides the operator an intuitive and interactive feeling of virtual or remote compliance and reactive forces [Mavroidis, et al, 2001]. The actuators of this system involve the use of a novel stiffness-controlled element employing electro-rheological fluids and electromagnetic mechanism. This actuator has the potential of inducing substantial forces, inducing large displacement, using a compact lightweight mechanism. Such an actuator can be applied to numerous areas including space, medical, military, entertainment, and others (see Figure 1). We are proposing herein to develop and demonstrate this novel actuator, which is the key element of the proposed task.

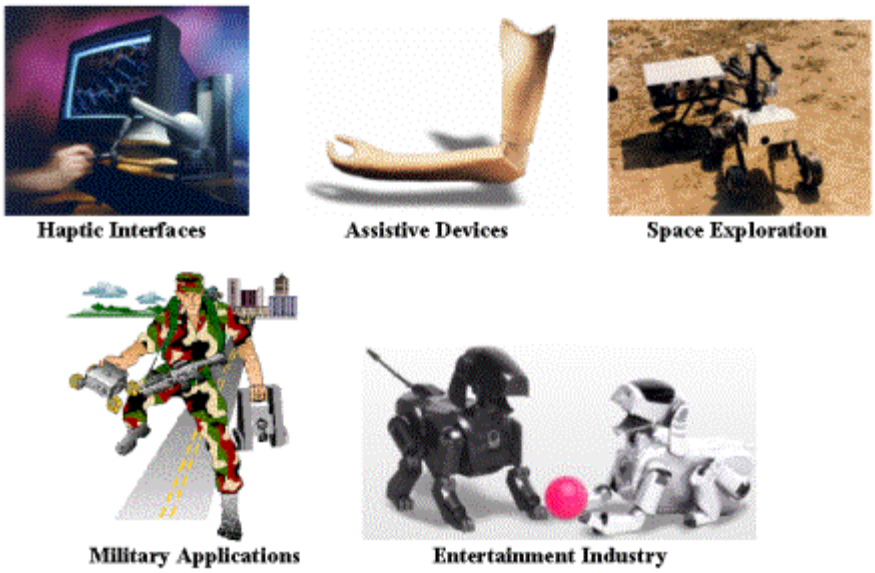
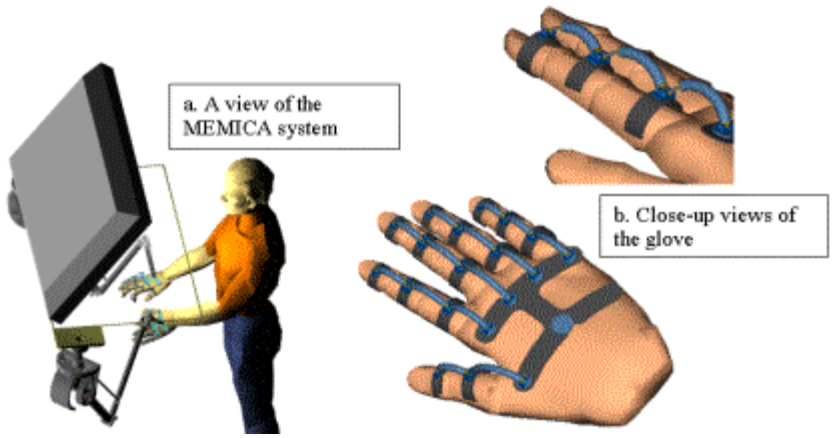


FIGURE 1: Several applications that will benefit from the proposed ECFS Actuator.

Advances in material technology have introduced lightweight and strong substances, making it possible to build structurally strong articulated mechanisms that are compact and weigh very little. However, conventional actuators, such as electric motors and hydraulic and pneumatic cylinders, prevent large reductions in the overall weight and complexity of the robotic manipulator. Electric motors are heavy, and since they run at high speeds and produce low torques, they require a reduction gear system to produce the needed torques that are compatible with the motion of most mechanical devices. This increases the weight and complexity and has the added disadvantage of elevated noise and friction. Hydraulic and pneumatic actuators are much lighter than electric motors for the same power capability. However, they require a complex system of pumps, pressurized chambers, pipes, and valves to hold the working fluid. These systems are often noisy and prone to leaks, which are troublesome and messy at the least and hazardous at the most. They also have lower operation speed.

The proposed actuator has a hybrid configuration consisting of smart fluids with electrically controlled rheological properties combined with electromagnetic actuation, so-called Electrically Controlled Force and Stiffness (ECFS) actuator. Such an actuator is expected to have a large force to weight ratio, induce large displacements, with a reaction time on the order of milliseconds. This type of actuator is ideal for our MEMICA system since it can control not only the developed forces but also their compliance and damping. This capability is the key to the development of our haptic system and a 3-D schematic of this system with its haptic gloves are shown in Figure 2. The proposed ECFS actuators, which will be developed in this proposed task, will actuate the joints of our proposed haptic glove. While the development of the full MEMICA system is outside the scope of this task we will, however, test the performance of ECFS actuators in a simple glove that will be demonstrated to operate as a force-feedback device.

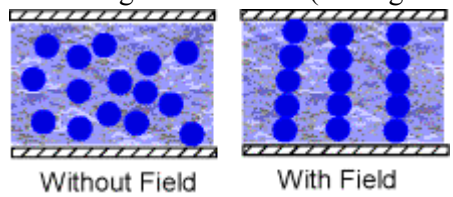
FIGURE 2: Detailed 3D Schematic of the MEMICA Haptic System and Close-Up View of the Glove.



3.1 ERF AS A BASIS FOR MEMICA ACTUATORS

Electro-rheological fluids (ERF) are fluids that experience dramatic changes in rheological properties, such as viscosity, in the presence of an electric field. Willis M. Winslow first explained the effect in the 1940's using oil dispersions of fine powders [Winslow, 1949]. The fluids are made from suspensions of an insulating base fluid and particles on the order of 0.1 – 0.01 μm (in size). The volume fraction of the particles is between 20% and 60%. The electro-rheological effect, sometimes called the *Winslow* effect, is thought to arise from the difference in the dielectric constants of the fluid and particles. In the presence of an electric field, the particles, due to an induced dipole moment, will form chains along the field lines (see Figure 3.)

FIGURE 3: Particle suspension forms chains when an electric field is applied on the ERF.



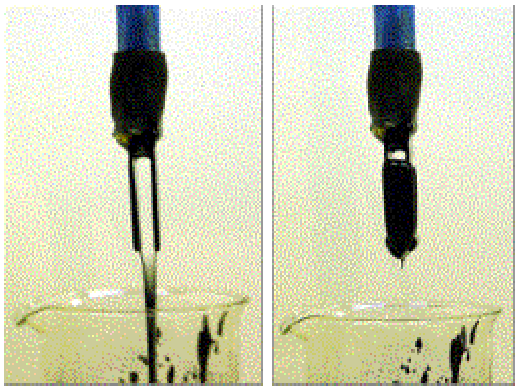


FIGURE 4: Electro-Rheological Fluid at reference (left) and activated states (right).

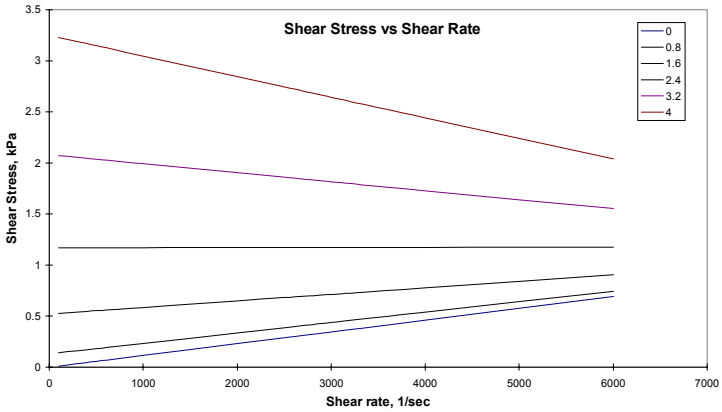


FIGURE 5: Relationship Between ERF's Shear Stress & Shear Strain Rate. [ER Fluid Developments Ltd, UK]

The structure induced changes the ERF's viscosity, yield stress, and other properties, allowing the ERF to change consistency from that of a liquid to something that is viscoelastic, such as a gel, with response times to changes in electric fields on the order of milliseconds. Figure 4 shows the fluid state of an ERF without an applied electric field and the solid-like state (i.e. when an electric field is applied). Good reviews of the ERF phenomenon and the theoretical basis for ERF behavior can be found in [Conrad, 1998].

3.2 THE TEAM'S MEMICA RELATED HERRITAGE AND CURRENT STATUS

During the last two years, the Rutgers University and JPL team has been involved in studies of novel ERF based mechanisms and their potential application to haptic interfaces in order to enable an operator to "feel" the stiffness/damping and forces at remote or virtual sites [Bar-Cohen et al, 2000 & Mavroidis et al, 2001]. The developed concept has two key aspects including miniature Electrically Controlled Stiffness (ECS) elements (see Figure 6) which make use of ERFs to achieve this feeling of remote/virtual compliance/ damping. The ECS element resistance to external loads is modified electrically by controlling the flow of an electro-rheological fluid (ERF) through slots on the side of a piston (Figure 6). The ECS element consists of a piston that is designed to move inside a sealed cylinder filled with ERF. The rate of flow is controlled electrically by electrodes that are facing the flowing ERF while it is inside the channel.

To control the "stiffness" of the ECS element, a voltage is applied between electrodes facing the slot, affecting the ability of the liquid to flow. Thus, the slot serves as a liquid valve, since the increased viscosity decreases the flow rate of the ERF and varies the stiffness felt. To increase the stiffness bandwidth from free flow to maximum viscosity, multiple slots are made along the piston surface. To wire such a piston to a power source, the piston and its shaft are made hollow and electric wires are connected to electrode plates mounted on the side of the slots. The inside surface of the ECS cylinder surrounding the piston is made of a metallic surface and serves as the ground and opposite polarity. A sleeve covers the piston shaft to protect it from dust, jamming or obstruction. When a voltage is applied, potential is developed through the ERF along the piston channels, altering its viscosity. As a result of the increase in the ERF viscosity, the flow is slowed significantly and resistance to external axial forces increases.

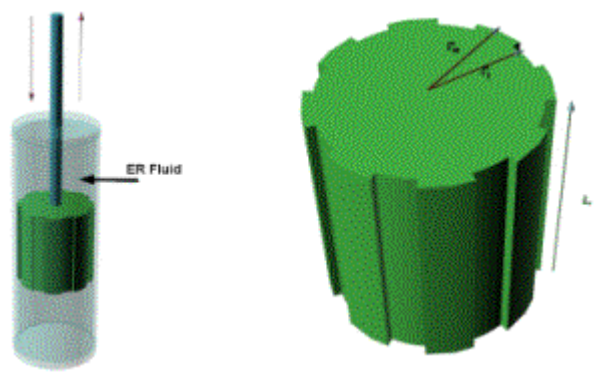


FIGURE 6: ECS Element and Its Piston.

To test the concept of controlling stiffness/damping with a miniature ECS element, a larger-scale testbed has been built at the Rutgers Robotics and Mechatronics Laboratory. This testbed is equipped with temperature, pressure, force and displacement sensors to monitor the ERF's state. Six system parameters are measured during experimentation: voltage, current, force, displacement, pressure and temperature. All sensor signals are interfaced directly to Analog-to-Digital boards located in a Pentium II PC and are processed using the Rutgers WinRec v.1 real time control and data acquisition Windows NT-based software. Representative results from tests are shown in Figures 7a and b. In Figure 7a no voltage is applied to the device. Four different weights equal to 2.75lb, 5.50lb, 8.25lb and 11lb are placed individually on the weight platform. A very fast descent of the piston is observed for all the weights. In Figure 7b, the same procedure is followed but this time a voltage of 2kV is applied on the ERF. It can clearly be seen that the piston is showing a very slow descent and for the lightest weight (i.e. the 2.5lb.) no motion is observed. This experiment shows that when the electrical field is enabled, the viscosity of the ERF is such that the ECS element can resist the gravity forces from the weights.

The design, modeling and testing of the ECS elements gave us a lot of experience that will be used in this project. While the ECS element was able to resist externally applied forces in an electrically controlled way, it was not able to generate forces (i.e. to "push" back). Therefore, a new actuator concept is needed to be able to generate controlled forces and on the same time be able to electrically control its compliance / damping.

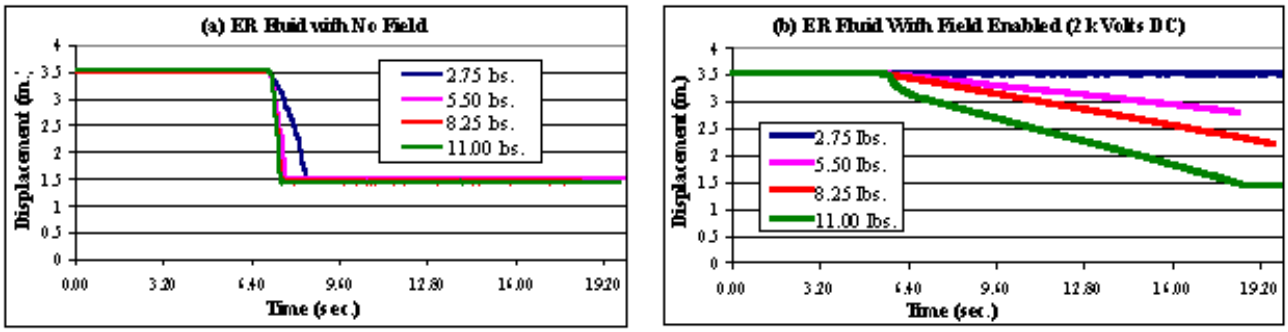


FIGURE 7: Piston Displacement.

4.0 APPROACH

The proposed task would lead to a demonstration of a MEMICA-base haptic glove at TRL 3. In this project we will design, fabricate and test Electrically Controlled Force and Stiffness (ECFS) Actuators composed of electro-rheological fluid elements and electromagnetic mechanism. We will also investigate the possibility of using these ECFS actuators in a haptic MEMICA glove with force-feedback. The proposed task will consist of the following research phases.

4.1 Phase 1: Computer Aided Design of ECFS Actuators

The proposed ECSF actuator is a small linear actuator that operates as an *inchworm* motor. Figure 8 shows a schematic of this inchworm motion. Motion is created through sequential activation of three elements. The outer two elements, act as clamps or brakes on the output shaft. The central element, the mover, expands and contracts along the output shaft when voltage is applied. Though all three elements operate independently, they are physically connected. When a voltage is applied to the brake on the left, it clamps the shaft. Then a variable rate voltage is applied to the mover, causing it to expand. This motion is transferred to the output shaft that moves on the left. At the end of the motion of the mover element, a voltage is applied to the brake on the right, causing it to grip the shaft. Voltage is removed from the brake on the left, releasing it from the shaft. An opposite sign voltage is applied to the mover, causing it to contract. When this motion is transferred to the shaft it moves again on the left. This process is repeated as necessary, inching forward (or backward) as an inchworm does in nature.

In the proposed ECFS actuators, the two brakes will be ERF-based cylinders similar to our ECS concept that was described earlier. The mover element will be composed of two electromagnetic cylinders that can attract and repulse themselves depending on the polarity of the current that passes through their windings. A schematic description of the ECFS actuator is shown in Figure 9. The actuator consists of two pistons (brake elements) and two electromagnetic cylinders (mover element). Similar to the ECS element concept, each piston has several small channels with a fixed electrode plate. When an electric field is induced between the piston anode and cylinder cathode, the viscosity of the ERF increases and the flow rate of the fluid though the piston channel decreases securing the piston to the cylinder wall.

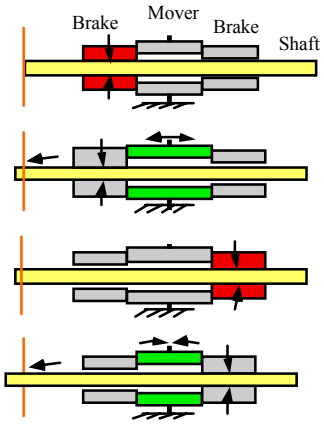


FIGURE 8: Concept of the Inchworm Motor.

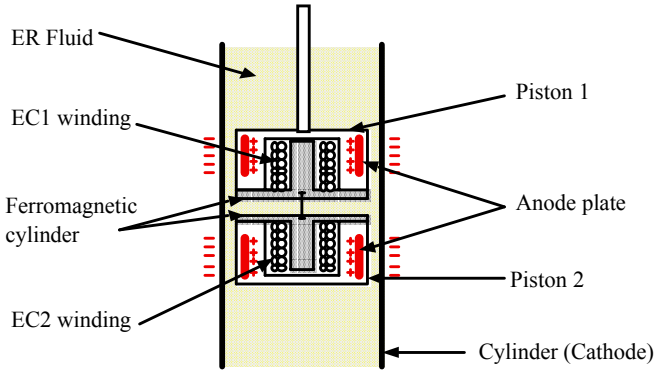


FIGURE 9: ECFS Actuator Configuration.

The electromagnetic translation mechanism consists of two cylinders with a coil and a ferromagnetic core integrated within the piston. When a current impulse is passed through the winding, an electromagnetic field is induced and depending on the current direction, the cylinder moves forward or backward. This actuation principle is shown as a set of sequence diagrams in Figure 10. In the first step, piston P1 is fixed relative to the cylinder by activating its electrode and applying a voltage on the ERF; then triggering the electromagnetic cylinder moves piston P2 forward. The ERF located between the two pistons is then displaced backward through the channels of piston P2. A horizontal channel is added at the surface of a ferromagnetic cylinder to increase the flow rate of the fluid. In the second step, the ERF in the channels of piston P2 is activated and P2 becomes fixed to the cylinder while P1 is disconnected from the cylinder. The current in the first winding is then reversed, changing the polarization of the magnetic cylinder, pushing P1 forward relative to P2.

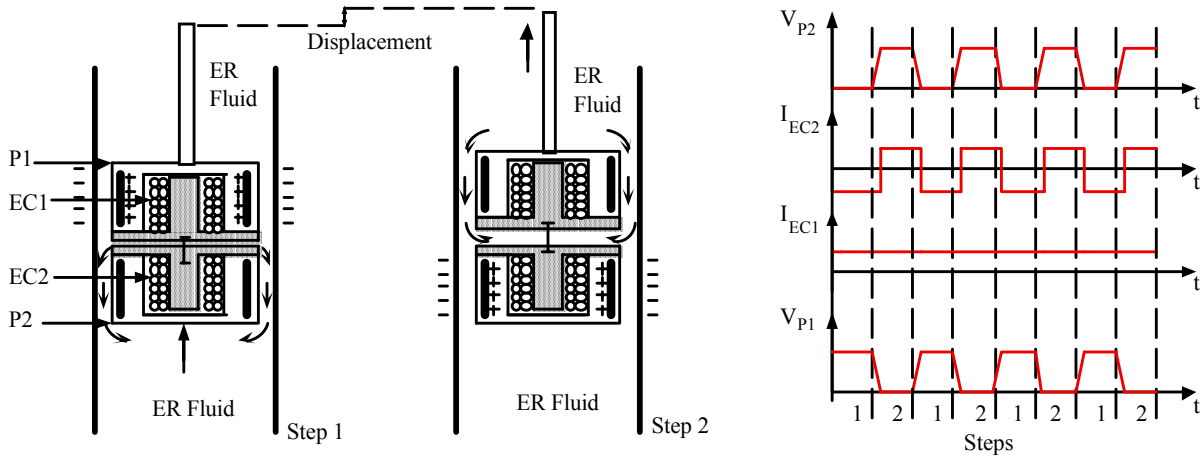


FIGURE 10: Sequence Diagram of ECFS Actuator Operation.

In this phase we will develop detailed 2D and 3D CAD drawings of the ECFS actuators using Pro-Engineer and Autocad and use these drawings in the modeling, simulation and fabrication phases.

4.2 Phase 2: Modeling, Simulation, and Performance Evaluation of ECFS Actuators

In this phase we will develop detailed analytical models that will calculate the forces produced by the brake and the mover as a function of the system geometry, velocity and acceleration; the voltage applied to the ERF; the current through the solenoids (windings); and the externally applied loads. These analytical models will be used to find optimal values for the actuator design parameters, to develop graphical animations and to evaluate the performance of the ECFS actuators.

The analytical modeling of ECFS actuators will follow the modeling methodology that was developed in our previous work for the modeling of the ECS elements [Mavroidis et al, 2001]. The analytical model will take into account various dynamic components that describe the dynamic behavior of ECFS actuators such as: a) the drag forces on the repelled / attracted piston; b) the drag force on the brake piston when this starts to move due to fact that the shear stress of the non-Newtonian ERF is exceeded; c) the forces on the brake piston from the ERF's yield stress in the static regime; d) hydrostatic and dynamic pressure forces; e) the magnetic forces produces by the solenoids; f) inertial and gravitational forces; g) frictional forces.

Once the analytical models describing the dynamic behavior of the ECFS actuators are developed, we will perform detailed parametric analyses to find optimal values for the geometry and operating conditions of the ECFS actuators. More specifically we would like to find out how the force and velocity outputs of the actuator change by changing the geometry of the pistons, the geometry of the solenoids, the voltage applied on the ERF on the brake element and the current that passes through the solenoids. The goal will be to find the values for these parameters that maximize the force and speed of the actuator while the voltage applied on the ERF and the total power consumption of the actuator are minimized and the manufacturing dimensions are within acceptable limits. Our calculations show that the voltage required to keep the brake element stationary under the force of 15N varies from the 2kV to 20kV as the outer diameter of the piston changes from the 3mm to 7mm. This analysis clearly shows that the piston geometry greatly affects the voltage requirements. It has to be noted here that the need of high voltage using the ERF's was expected. However, as it was demonstrated with our previous ECS prototype that a low power, small size circuit can be used to generate the required high voltage using a very low current in the order of micro-amps. Consequently, the re-

quired power is extremely low, in the order of mWatts. Similar studies will be performed for all design parameters. The mathematical analysis software package MATLAB will be used in this phase.

Once the parametric analyses are completed and ranges of acceptable values for the important design parameters and operating conditions are selected we will perform graphic simulations of the ECFS actuators. These animations will help us visualize the performance of the ECFS actuators. For these simulation experiments we will use the Virtual Reality software package WorldToolKit (WTK). WTK, which is already installed at Rutgers University, is a development system for building real-time 3D applications, including virtual reality simulations. World Tool Kit has a library of over 1,000 functions written in C that allows rapid development of virtual reality applications.

The final goal of this phase will be the performance evaluation of the ECFS actuators. We would like to be able to predict the force and velocity outputs, the efficiency and power needs and the force to weight ratio of ECFS actuators as a function of their size and system electrical inputs (ERF voltage and solenoid current). Based on our preliminary models, we have estimated that a representative ECFS actuator with 1cm diameter, ERF voltages in the order of 2-5kV and solenoid currents from 200-300mA will move forward or backward with very small displacement (<1.5mm) with a total displacement capability of at least 30mm. The duration of each cycle can be close to a millisecond, corresponding to the response time of the ERF. The ECFS actuator can then reach a speed higher than 15-cm/s with a piston displacement equal to 0.5-mm at 3-ms cycle duration. Such an ECFS actuator can develop a force in the order of 15N.

Figure 11 shows a qualitative comparison of the ECFS actuators to conventional DC motors, hydraulic and pneumatic actuators and Shape Memory Alloy (SMA) actuators. The data for the ECFS actuators have been calculated using our preliminary data while the data for the other actuators have been found in [Burdea, 1996]. ECFS actuators will be lightweight actuators with high force to weight ratio. They will have twice the force output of DC motors for the same motor size. They will have the same force output as pneumatic actuators for half the actuator size. In addition they won't require all the additional components that pneumatic actuators do such as air supplies and tubes. ECFS actuators won't be able to develop the high force to weight ratios that hydraulic and SMA actuators achieve. However ECFS actuators won't have the detrimental disadvantages that SMA and hydraulic actuators present. SMA actuators are very slow with very low energy efficiency (less than 1%). ECFS actuators will be very fast with an estimated energy efficiency of 30%. Hydraulic actuators are very large in size, relatively slow, very noisy and prone to leaks. ECFS actuators have none of these disadvantages.

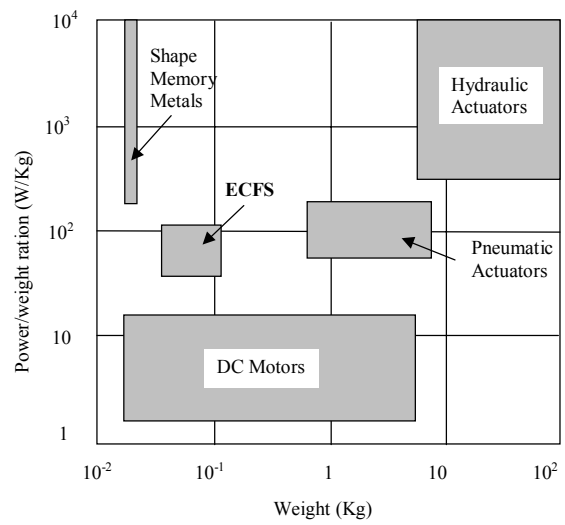


FIGURE 11: Actuator Comparison Based on Weight and Output Power to Weight.

4.3 Phase 3: Fabrication of ECFS Actuator Prototype

In order to demonstrate the validity of the ECFS actuator concept and evaluate experimentally the performance of such actuators a prototype will be fabricated and a preliminary drawing and the components of the ECFS actuator is shown in Figure 12. An electronic controller will be designed and fabricated to operate synchronously to power the ECFS prototype. The electronic board will have several functions including, high voltage generator, current generation and load cell amplification. A pulse with modulation amplification having a frequency of 200Khz will be used to drive the current in the electromagnetic coil in order to reduce heating. The ERF power system will be a low power circuit that will generate high voltages with a very low current. It has been inspired from a similar small supply circuit originally designed for night vision scopes. This power supply is capable of producing 4.5-KV from a standard 9-V battery. By modifying this circuit to produce a PC adjustable straight DC voltage, linear control of the viscosity will be implemented with programmed software control. This power system allows for portability in later prototypes. All the interface and control circuitry will be housed in a portable ventilated enclosure.

A miniature load cell with a strain gage will be mounted on the lower extremity of the cylinder to measure forces that are generated by the ECFS actuator. Displacement and acceleration sensors will also be included for position, velocity and acceleration measurements. Hall Effect Transducers will be considered as displacement sensors for their accuracy, compact size and zero friction. The electronic board and all sensors will be interfaced to a PC using the Rutgers reconfigurable control architecture called WinRec v.1.

Once the ECFS actuator prototype is developed, a 4-bar mechanism will be constructed integrating this actuator to power one of its joints. This 4-bar mechanism will be a simple exoskeleton one-finger force-feedback device as it is shown in Figure 13. This mechanism will demonstrate the possibility that ECFS actuators can be used as lightweight, powerful actuators in haptic systems. The actuator will be placed out of the way of grasping motions, on the back of the finger as shown in Figure 13. The natural motion of the finger will be then unrestricted. To accommodate a large number of finger sizes and geometries the 4-bar mechanism will be mounted on an adjustable ring. The adjustable ring will be made of two flexible metal strips assembled with Velcro. Once the Velcro attachments are closed, the strips form a very rigid ring. The rigid ring will be able to support large forces without being distorted and without risk of pain or stagnation of blood in the presence of large forces.

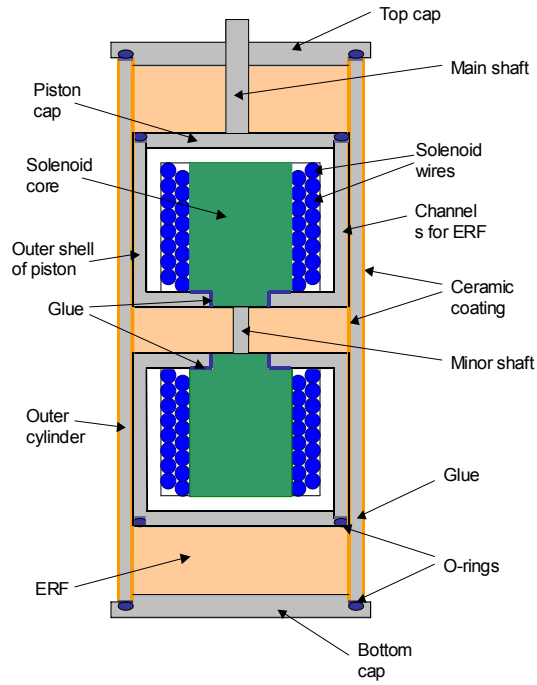


FIGURE 12: Cross-section of the ECFS actuator prototype.

4.4 Phase 4: Testing of ECFS Actuator Prototype

A series of tests will be performed to evaluate experimentally the performance of ECFS actuators and their ability to be used as motors in force-feedback devices. The tests will consist of open and closed loop position and force control experiments of the ECFS actuator alone and closed-loop force feedback experiments using the one-finger haptic device that will be actuated with the ECFS actuator.

The open loop control experiments will consist of applying a series of current inputs to the solenoids while a voltage is applied on the ERF of the brake. The goal here is to observe the motion and force capabilities of the ECFS actuators when they are moving one step only. Various types of commands will be used such as step, ramp, sinusoidal and pulse inputs. Based on the type of commands, a computer will control which element is the brake and which is the mover so that there will be an alternation of which piston is under ERF voltage. These tests will include not only position tests where the mover element is freely moving under the current input, but static force experiments as well, where the mover element is stalled and the applied force is measured. Once the motion and force properties of the ECFS actuators are studied for one step, we will perform open loop tests where a desired position or time trajectory of the actuator output shaft is selected that will require several steps. Then, using our knowledge from the previous experiments, a series of solenoid current and ERF voltage inputs will be calculated that will be able to bring the shaft to the desired location through a series of steps. During these open loop tests we will be measuring the position, velocity, acceleration and force of the ECFS actuators. These results will be used to verify the models of ECFS actuators derived in Phase 2. They will also be used to evaluate the performance of the ECFS actuators by experimentally calculating its accuracy, efficiency, bandwidth, repeatability and non-linear behavior.

The closed-loop control experiments will consist of selecting desired position or force command inputs to be produced by the ECFS actuator. Then using position or force feedback the control error will be calculated that will be processed by a controller. Initially will use simple PID or linear state-space-controllers. The gains will be selected using optimal and/or robust control design criteria. Adaptive or non-linear controllers will be considered if the closed loop performance of the ECFS actuators under the previous controllers is not acceptable. Robustness tests will also be performed where different payloads are attached at the end of the actuator shaft.

Finally, experiments will be performed using the ECFS actuated one-finger haptic device. The experiments will consist of commanding the haptic device to generate forces on the finger of a human operator. These generated forces will correspond to a force developed in a virtual environment. We will test the mirroring of both rigid and soft surfaces. For the latter ones, the unique capabilities of the ECFS actuator to control its damping and stiffness characteristics will be tested. Different human factor tests will be performed when evaluating the operation of this one finger mechanism. We will evaluate the comfort, the adaptability and the resistance feeling with different users, and also the accuracy of the applied force/resistance.

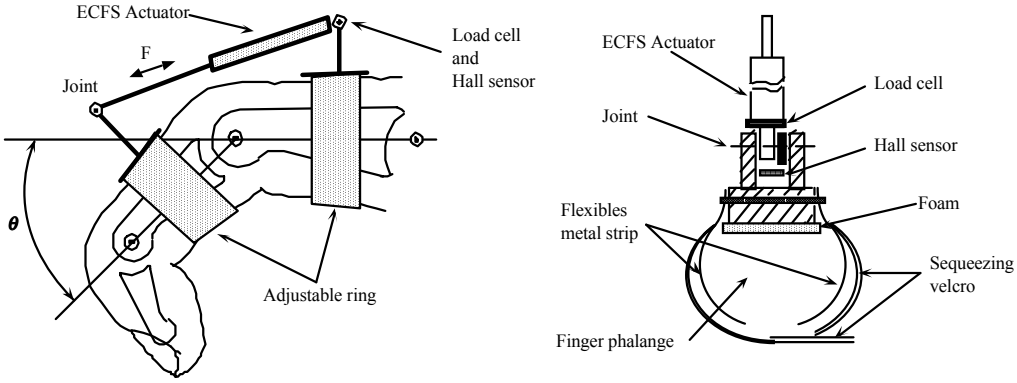


FIGURE 13: Illustration of the Mounting of an ECFS Actuator on the Finger Phalange.

4.5 Phase 5: Construction of a Demo MEMICA glove

Upon the completion of the demonstration of the ECFS actuation of one-finger, a full-glove with such actuators will be constructed and tested in various operation configurations both in operating action enhancer and as simulator of remote mechanical stiffness conditions. We will prototype a complete haptic glove with 16 actuators: 3 actuators for the thumb (2 for the flexion motion and 1 for the abduction/adduction motion), 4 actuators for the index (3 for the flexion motion and 1 for the abduction/adduction motion) and 3 actuators for the three other finger (flexion only). Figure 2 contains 3D drawings of the exoskeleton glove showing the positioning of all actuators on the fingers. For precision grasping with the thumb and the index finger, where abduction/adduction motion is involved, it is necessary to integrate actuators that would resist this motion.

To accurately measure the position and movement of the fingers, we will integrate angular or linear sensor on each ECFS actuator of MEMICA glove. Hall Effect Transducers will be considered for their accuracy, compact size and zero friction. A kinematics model and a calibration process will be developed for MEMICA glove to accurately match different users hand with the virtual hand. To assure high reliability of the MEMICA, issues related to sensor errors and sensor noise will be addressed during this phase. Efforts will be made to compensate for sensor errors using our model-based close loop system. Further, sensor noises will be eliminated by designing digital filters that will filter high frequency noises from all signals.

5.0 REFERENCES

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MEMICA Project

MEchanical MIrroring using Controlled stiffness and Actuators

- Seeks to develop a wearable haptic device for use in Virtual Reality and Tele-Robotics for Space Exploration Using ERFs

- Force/Touch interface
  - Enhance Human-Machine Interaction.
- ERFs allow for accurate mirroring of compliance

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