Compact Hybrid Actuator Project

Phase I

Presented at DARPA Smart Structures Technology Interchange Meeting

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SRC - Compact Hybrid Actuator Project - Phase I

a) Background

(1) Project start date: June 2, 2000

(2) Phase I duration: 18 months

b) Major Task - High Level Schedule

(1) Demonstrate PLMC Array Proof of Concept System - Yr. 1

(2) Develop Rolling Flexure Actuators (RFA) (for integration with PLMC) Yr. 1

(3) Integrate PLMC hot gas supplies and RFA (or pneumatic cylinders) - Yr. 2

(4) Integrate PLMC-Phase Change Supply with RFA - Yr. 2

c) Work completed to date

(1) New PLMC and PLMC-arrays test system and and equipment being designed (some equipment has already been procured)

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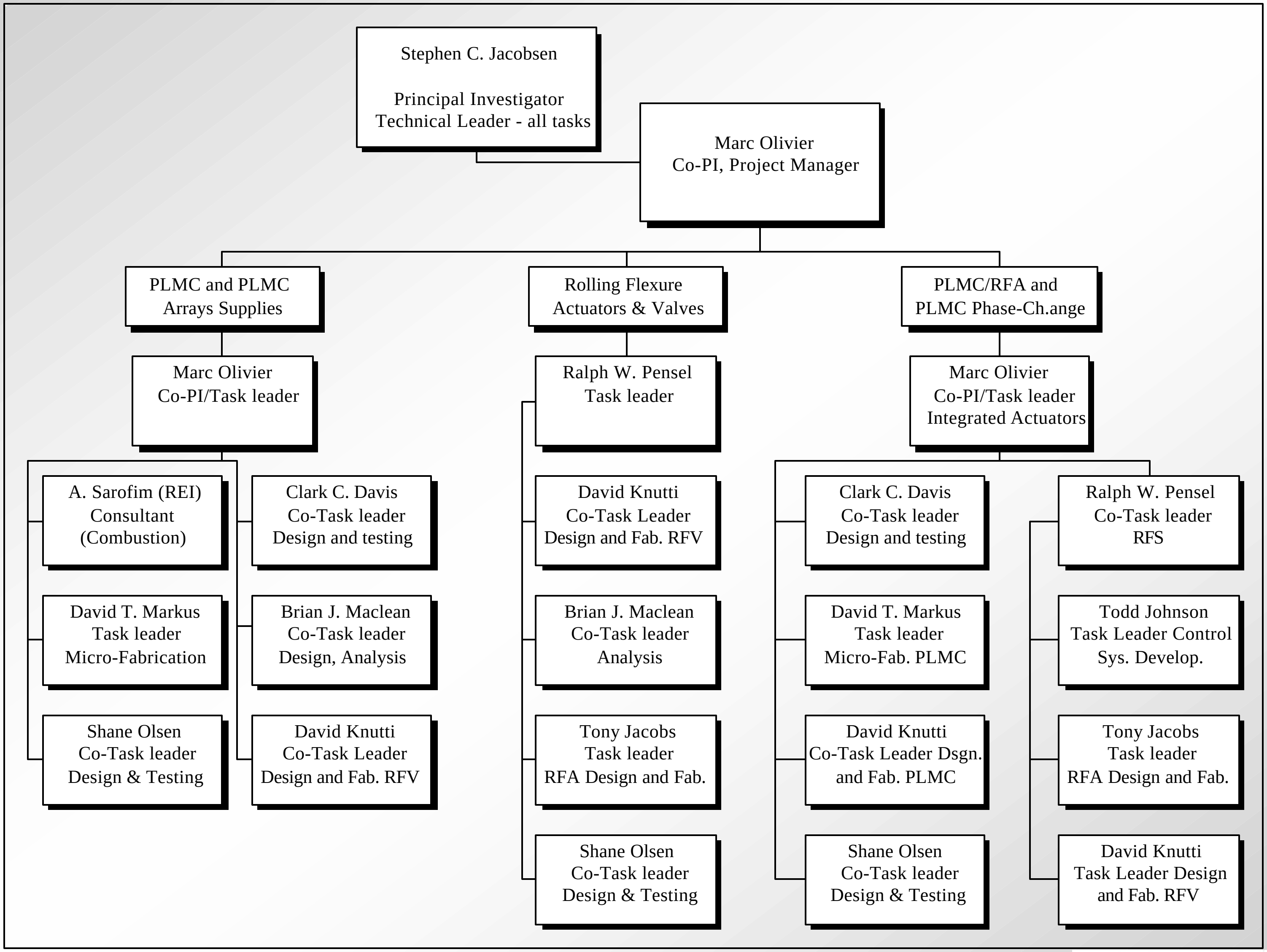
SRC - CHAP Project Team



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SARCOS RELATED EXPERIENCE

- Hydraulic Actuation Systems
- Pneumatic Actuation Systems
- Electronic Actuation Systems
- Advanced Sensors
- Human Kinematics
- Soft Tissue Interfaces
- Exoskeletal Robotics
- Control of Human Amplifier Systems
- Packaging Wearable Equipment
- Nonplanar Micro Fabrication Approaches

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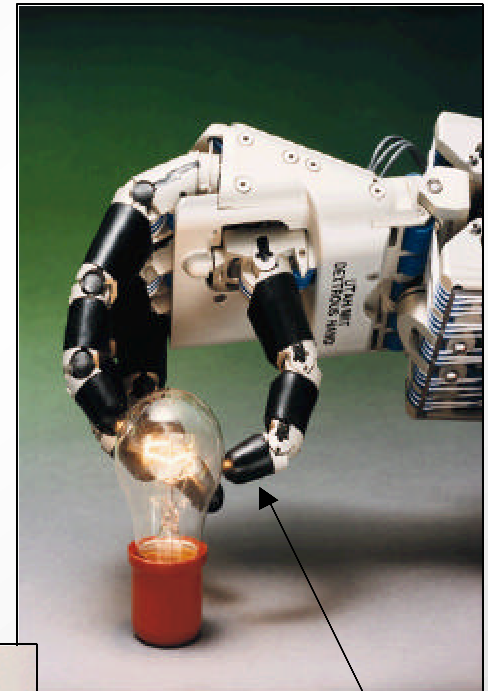
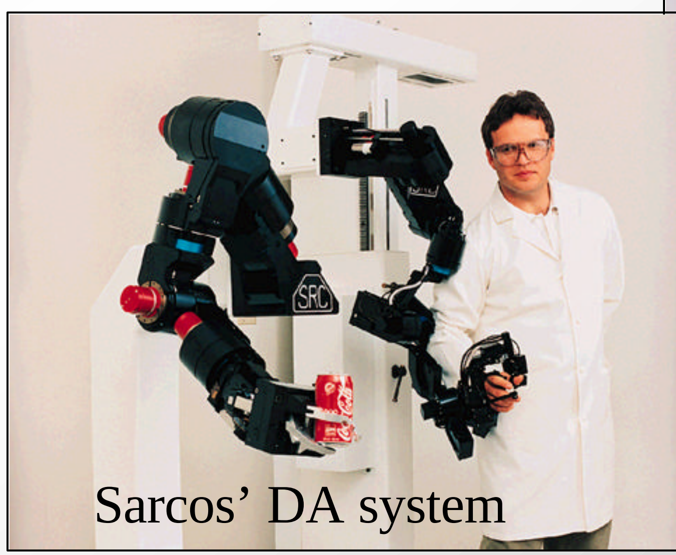
Hydraulic and Pneumatic, Complex Systems



Finger - Tactile sensor array



Sarcos' DA system

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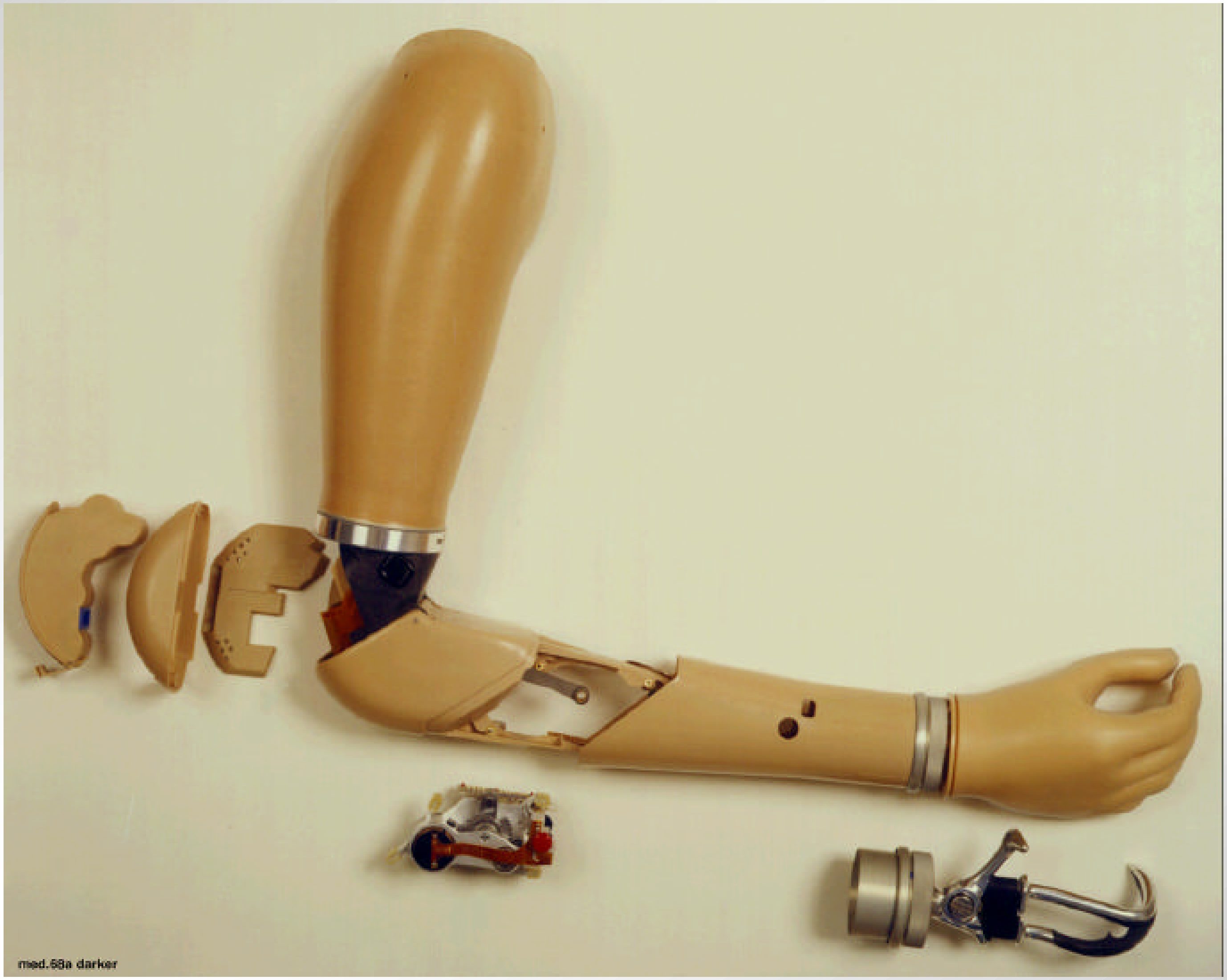
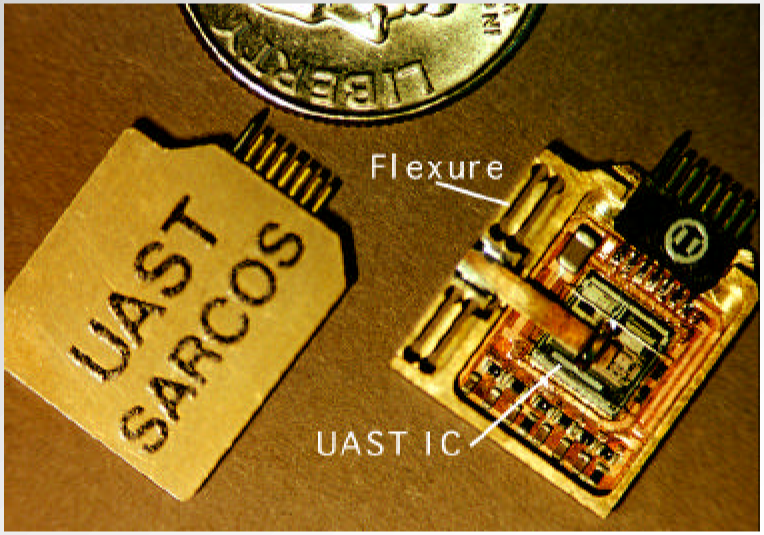
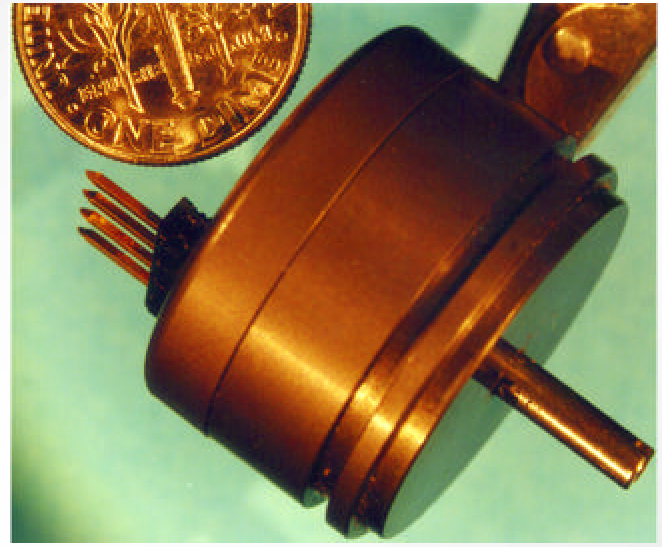
Electric Systems - Prostetic Arm



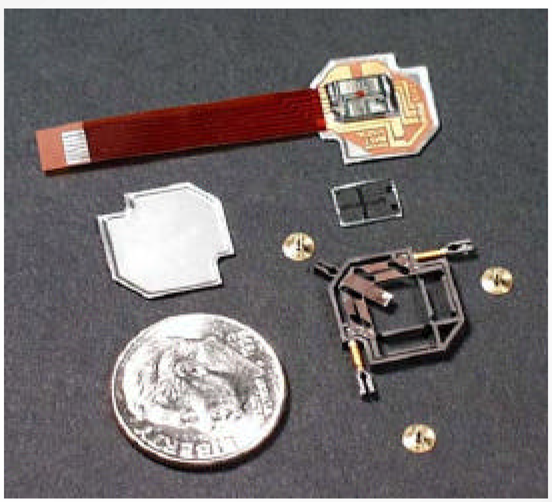
MEMS - Strain Transducer and Rotary Encoder



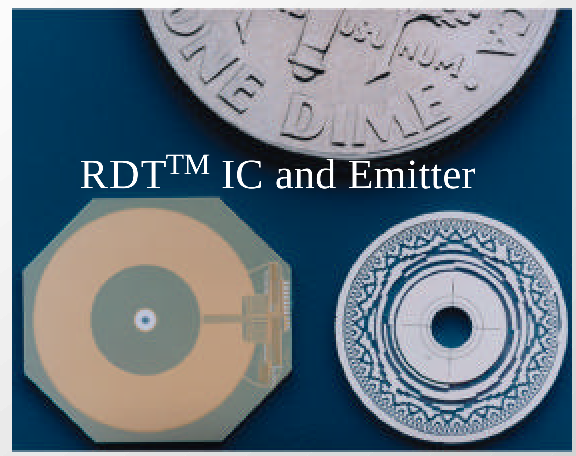
UniAxial Strain Transducer (UAST^{TM})



Packaged Rotational Displacement Transducer (RDT^{TM})



BiAxial Strain Transducer (BiAST^{TM})



RDT^{TM} IC and Emitter

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Sensor Suit - Motion Capture System

- **Sensor Suit® - passive exoskeleton**
  - » Measures 32 DOF (legs, upper body, arms and head)
  - » Can be used to create database of human joint kinematic in representative infantryman operations
  - » Provides testbed to evaluate interfaces to soft tissues
- **Physics-based Dynamic Simulation (using human kinematic database)**
  - » Used to evaluate torque/power requirements for various notional SES concepts (e.g. for different power/actuator and structures)
  - » Used to create database required to estimate loads on SES structure

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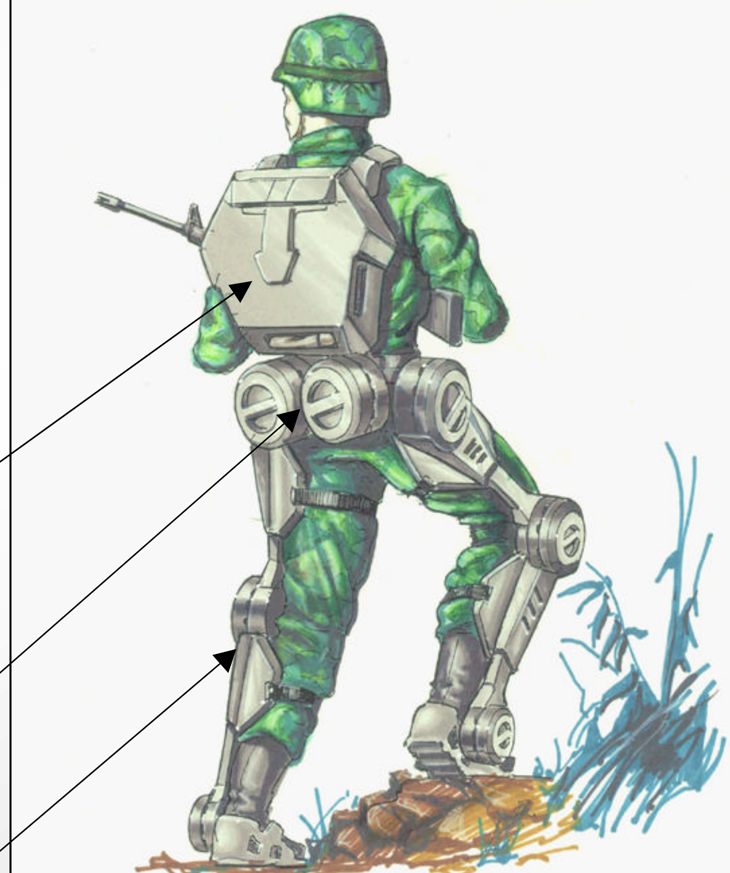
System Kinematics and Configuration

- System Configuration Options
  - » Base System: Legs and torso (tethered or driven by ambulatory power source)
  - » Option 1: Base system with neck and head
  - » Option 2: Base system with arms and hands

Torso mounted ambulatory power source

Optional tether to power source

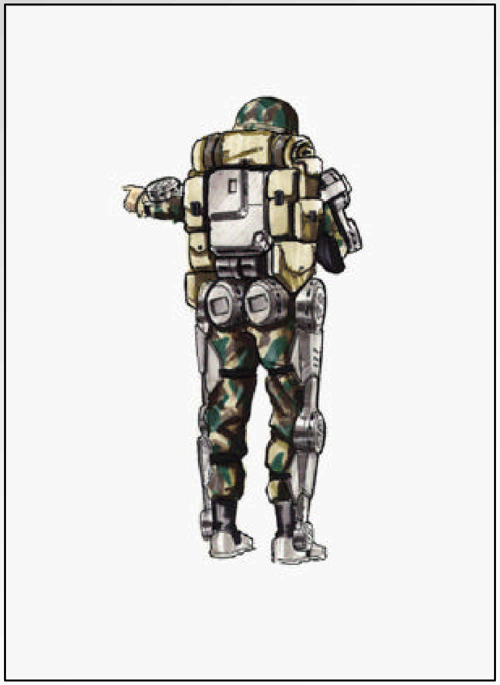
Legs (8 DOF)



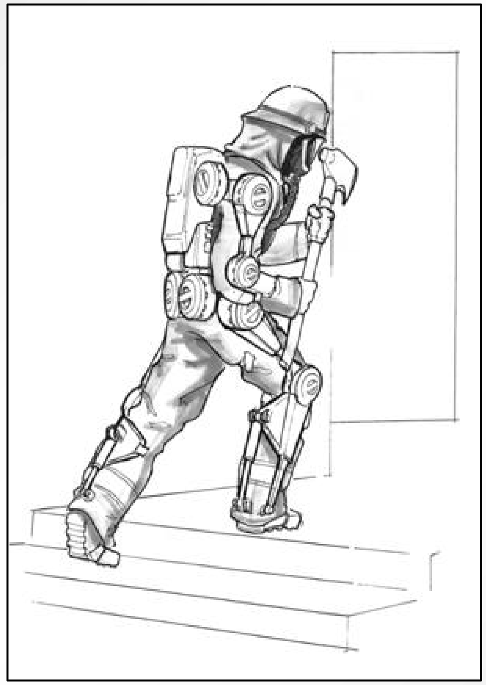
Exoskeleton Base Unit

EHPA Application Specific Packages (II)

Applications of Untethered EHPA



Soldier Mule



Fire/Chemical Protective suit

Body Armor

Control

Control Strategy (baseline)

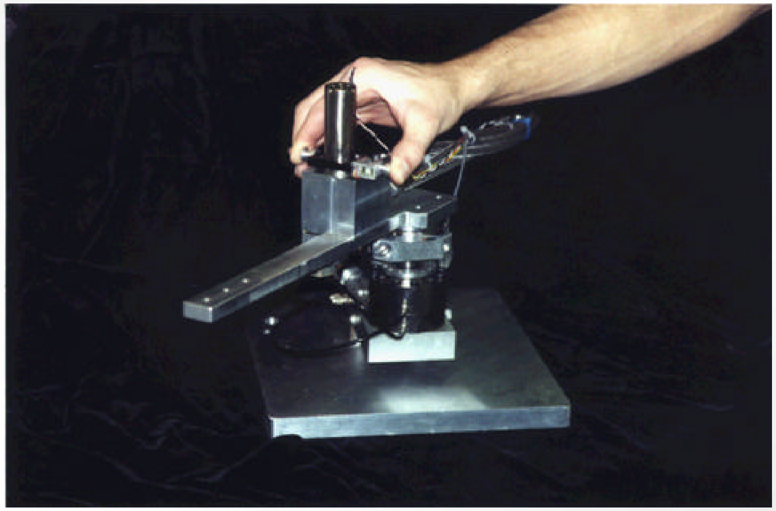
- Minimize load on the operator - “Get out of the way” or “Multi-dimensional power steering’
- Facilitate donning/doffing and ensure safe operation of the system. Self standing mode with gravity compensation

Approach

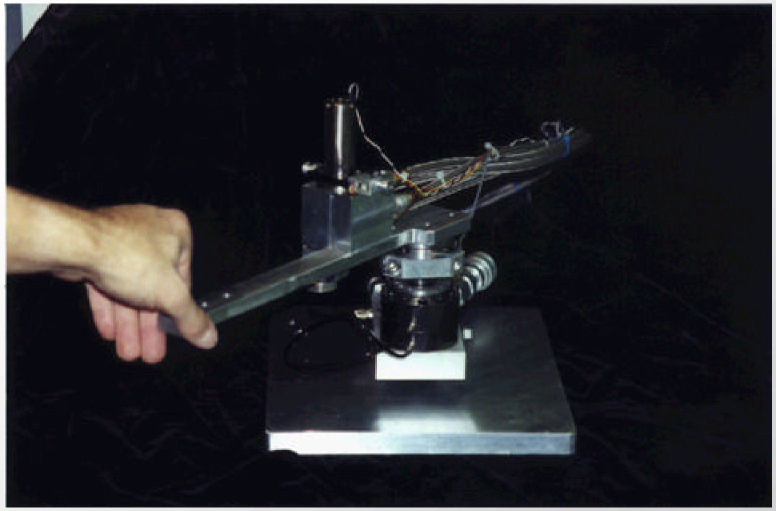
- Measure force/torque applied by the operator and control actuator to keep the reaction force on the operator low.

Demonstration

- Hydraulic Man-Amplifier - torque sensor used to monitor operator force and actuate hybrid jet pipe servo valves
- Servo-valves can also be manipulated directly to achieve all mechanical amplification



User directly moves hydraulic servo-valve



Man-Amplifier - electronic control of actuator

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Packaging Wearable Equipment

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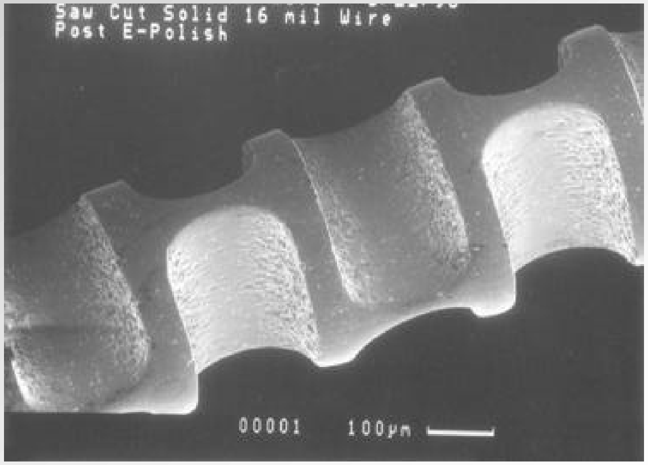
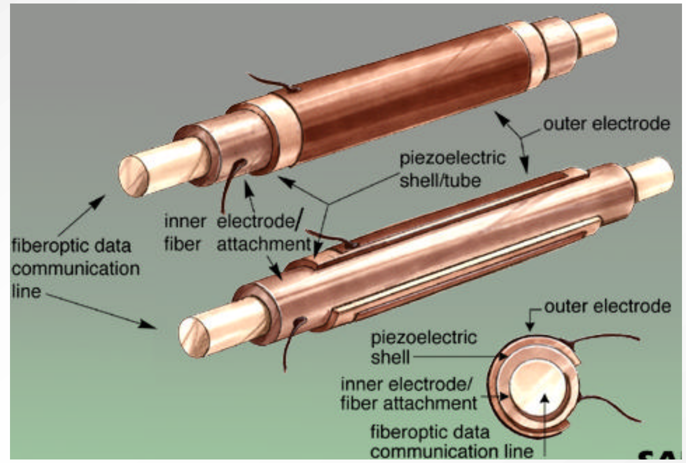
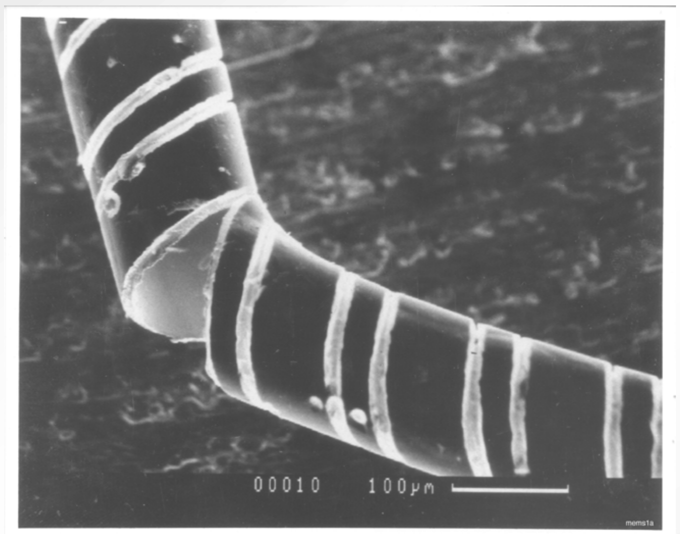
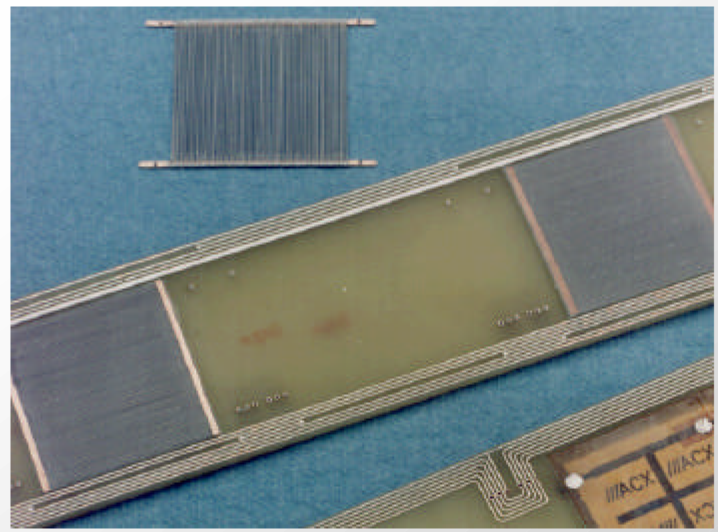
Non-planar Micro-Fabrication









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Problems with Actuators and Sensors

1. Motion Ranges and Speeds
   - a - Small Motions Tough To Scale Up
   - b - Fast Motions Tough To Reduce

2. Transducers Have Problems - They Don't Go Away
   - a - Reduction Paradox
     - Impedance Goes Like R**2
     - Losses, Backlash, Stiction
     - Cost, Reliability, Weight, Size
     - Dynamic Range, Noise

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Sensor and Actuator Properties - Many

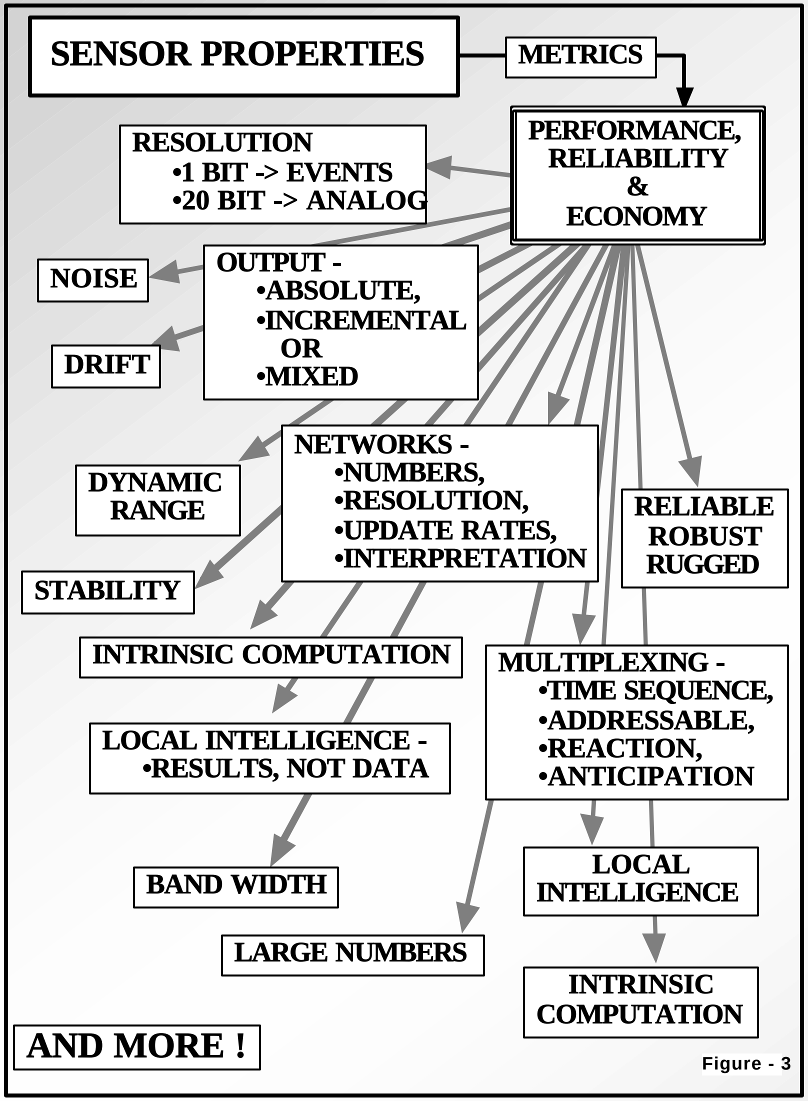

Figure - 3

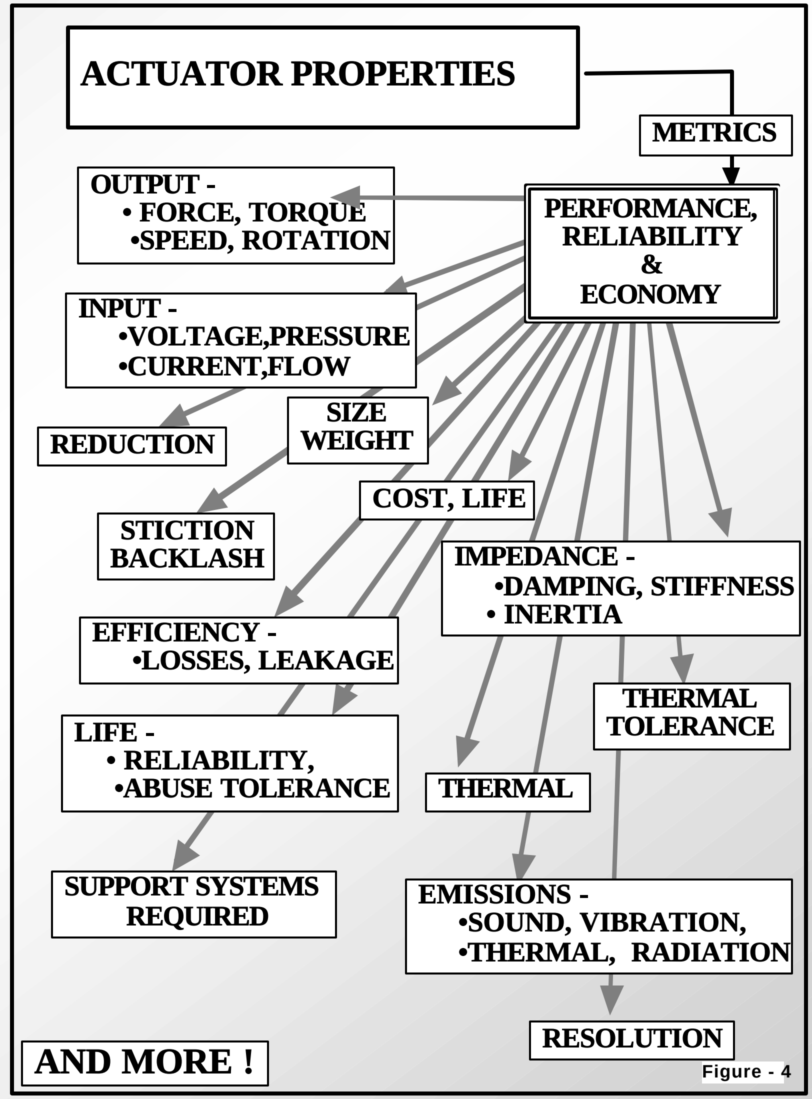

Figure - 4

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Objectives of SRC-CHAP

- Develop and Demonstrate a New Class of Compact, High Performance, Combustion-based Actuation Systems:
  - » Biologically inspired architecture - but very different building blocks
  - » Exploit arrays of micro-combustors (Pulsatile Linear Micro-Combustors) to produce hot gas and modulate power output at the source.
  - » Combined with a new type of Output Device (pneumatic or hydraulic) - Rolling Flexure Actuators and Valves

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Impact of New Compact Actuation Systems

Will Change Military Capabilities In Many Ways

(1) May be used in Wearable Energetically Autonomous Systems to increase load carrying capability (weapons, munitions, armor, and other application specific packages); increase mission range, mobility and speed.

(2) Can be used and other energetically autonomous systems such as robots and telerobots, aerospace systems, underwater systems.

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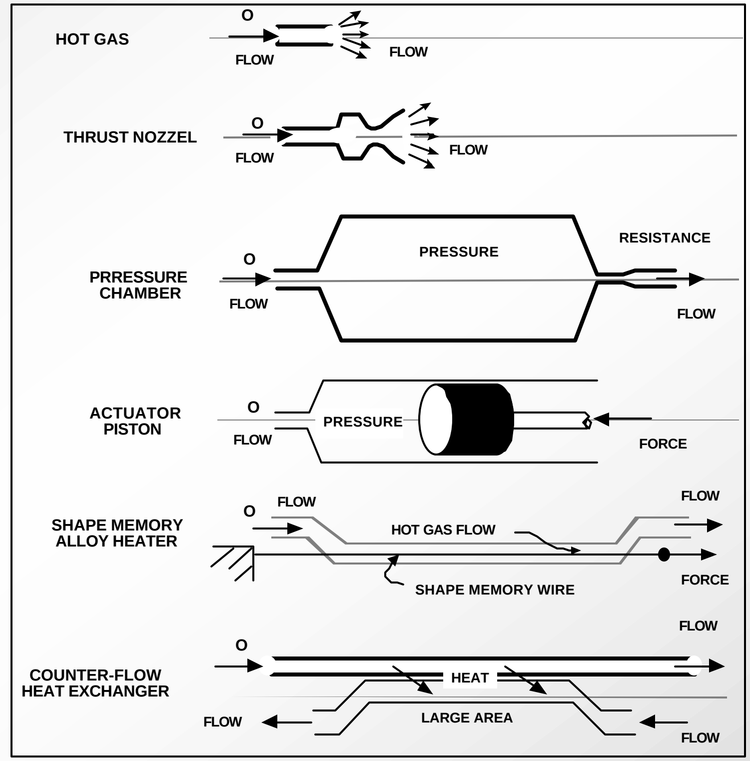
PULSATILE LINEAR MICRO COMBUSTORS (PLMC)

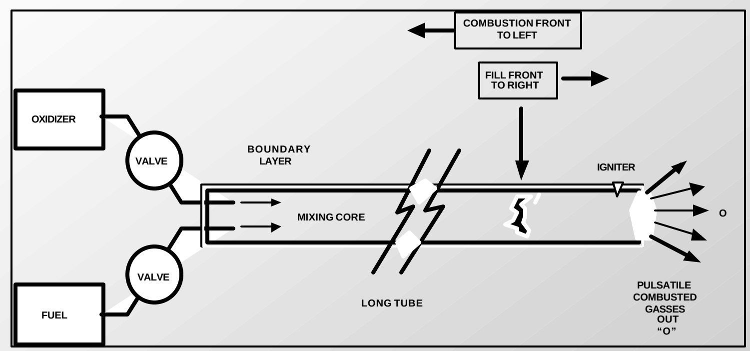
- Basic Concept
- Experimental Objectives
- Various Combustion Chambers
- Fluid-based Actuation Systems
- SMA-based Actuation Systems
- Resonance-based Actuation Systems

Micro-Combustion-based Energy Supplies

New compact energy supplies for Energetically Autonomous Systems

- New approach is similar in architecture to biological systems
- Energy supplies are built around arrays of Pulsatile Linear MicroCombustors (PLMC)
- Individual PLMC designed to operate at optimal efficiency in an oscillatory mode
- Controlled Proportional Output achieved by recruiting PLMCs as a function of numbers, time and frequency
- PLMC can be used to produce
  - » hot gas (for actuation of pistons, turbine, etc.), or
  - » heat which in turn may be used to induce phase change, drive thermoelectric elements or other heat engines.





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Operational Parameters

- **Operational Parameters - to date**
  - » Fuel-Oxidizer (F/O): acetylene-oxygen
  - » F/O equivalence ratio: 0.5 (fuel lean) to 3.2 (fuel rich)
  - » Flow rate: < 30 scc/min.
  - » Unburned fuel pressure: 1 atm.
  - » Combustors: 1 to 8 cm long, 500 microns ID
- **Operational Parameters - Planned**
  - » Fuel-Oxidizer (F/O): acetylene, hydrogen, methane/ethane, propane, butane and others.
  - » F/O equivalence ratio: from fuel lean to fuel rich flammability limit
  - » Flow rate: up to approximately 300 scc/min. (depending on fuels)
  - » Unburned fuel pressure: up to 10 atm.
  - » Combustors: 1 to 8 cm long, 500 microns to 2 mm ID (variable cross-section geometry).

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Experimental Set-ups 1

- **Four Combustion Chambers**
  - » Variable length 500 microns ID, glass and fused silica combustor
  - » Planar 2 cm x 500 microns (square section) high pressure combustor - Ground on Aluminum (Steel, Saphire ?)
  - » 2 cm long x 500 microns ID, fused silica combustor with inlet/outlet valves.
  - » 8 cm long x 500 microns ID, high pressure fused silica combustor
- **Igniters**
  - » External coils
  - » Heating source surrounding combustor
  - » Electric discharge (spark)
  - » Autocatalytic ignition
  - » Self-ignition

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Experimental Set-ups 2

- Computer Controlled Mass Flow Controller (MKS)
- Adjustable Inlet and Outlet Valves
- Flow restriction ports
- Optical Sensing Ports
- High Temperature Pressure Sensors
- High speed video camera (8000 fps, 1/40,000 sec shutter)
- Temperature sensors
- Fuel/Oxidizer preheaters
- Combustion Chamber Outer walls temperature control
- Combustion by-products chemical sampling and analysis (MS and FT-IR spectroscopy)

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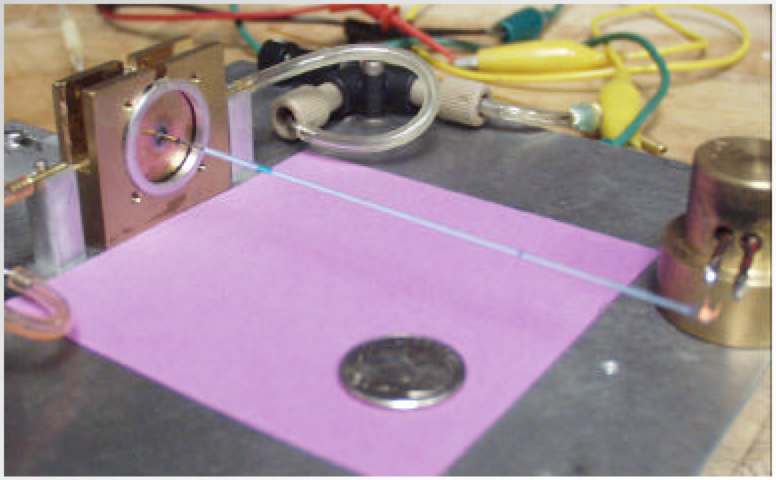
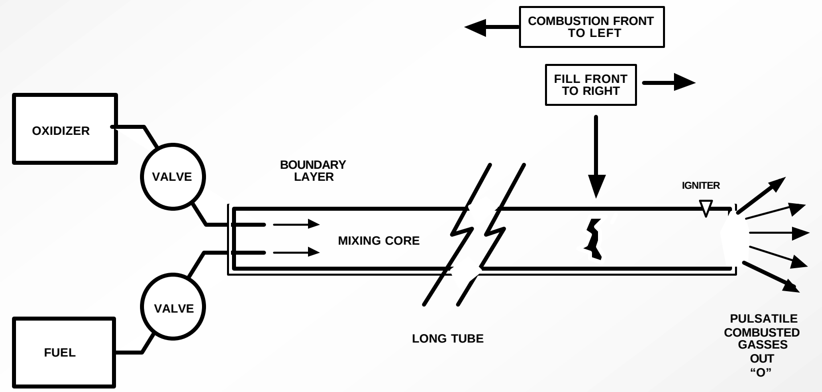
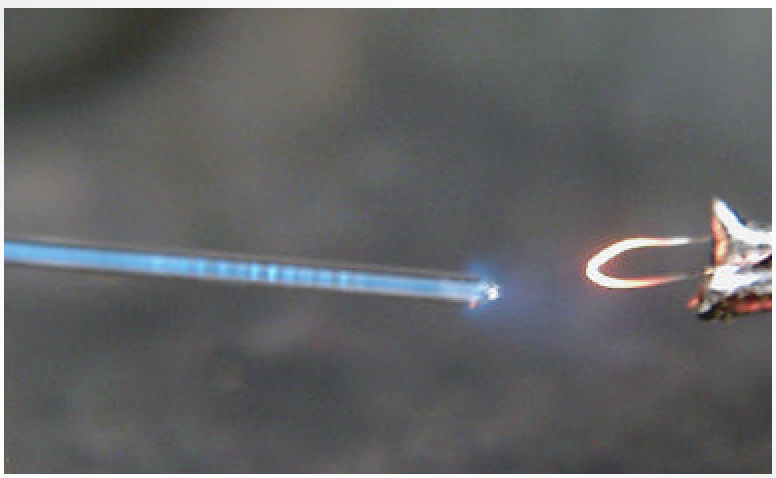
PLMC Principle of operation and Test Set-ups



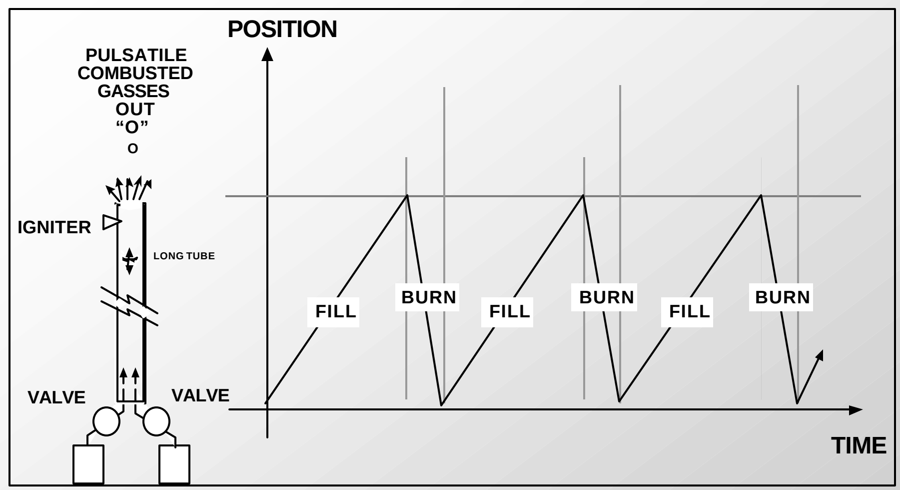
PLMC Test Set-up (1)



Schematic Representation of a PLMC



Flame Propagation in PLMC



Typical Fill/Burn cycle in PLMC

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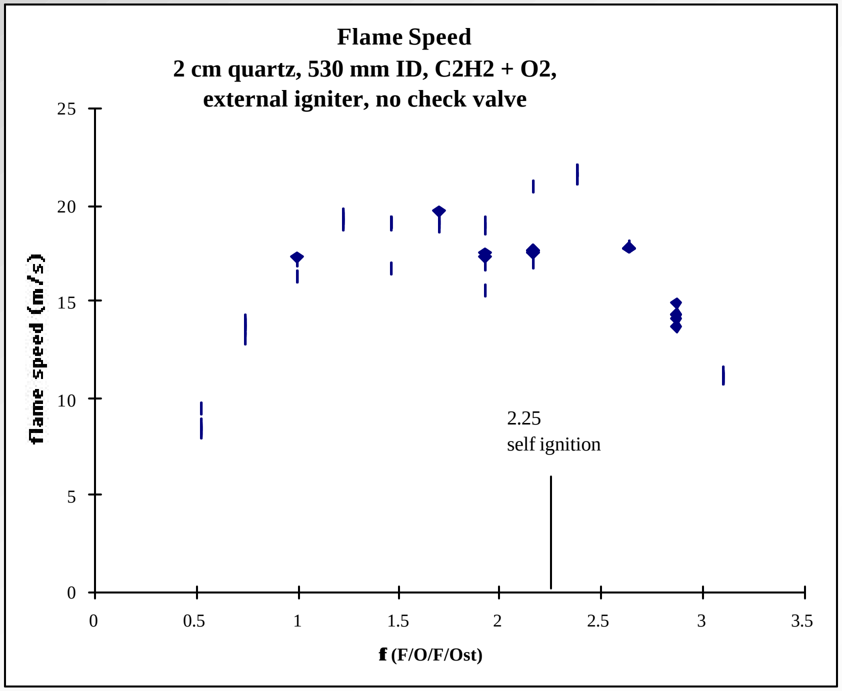
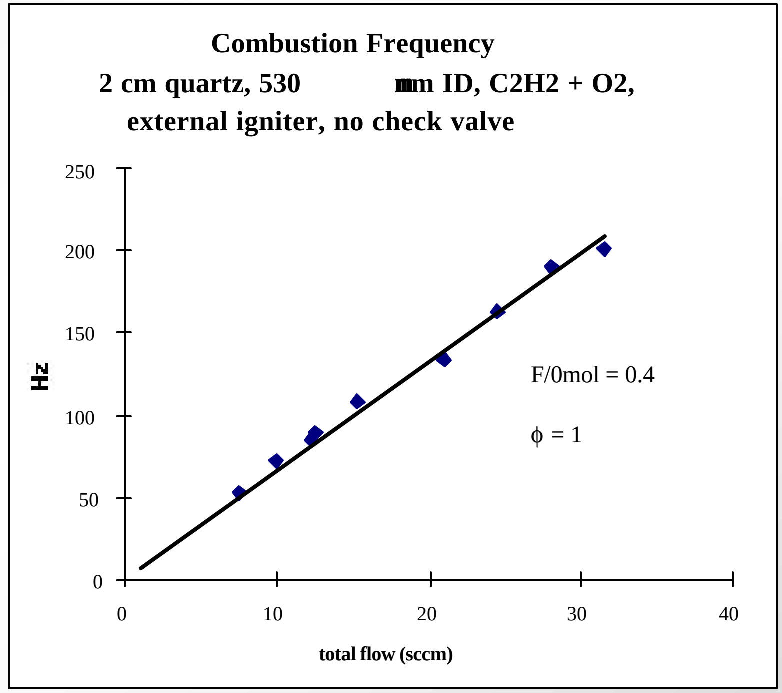
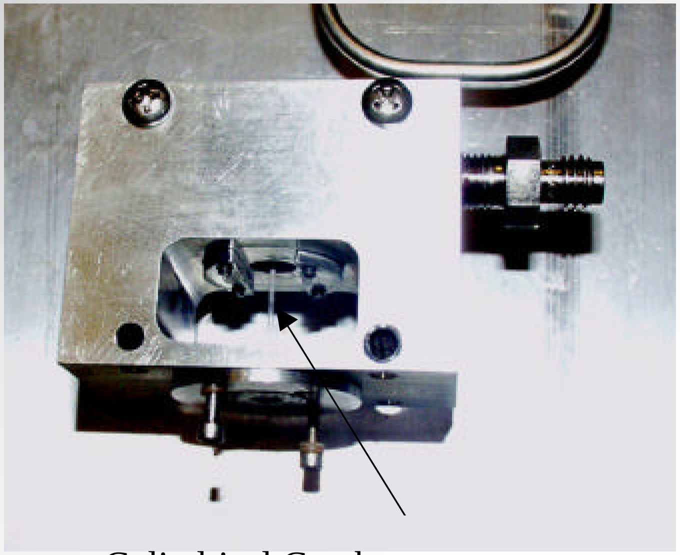
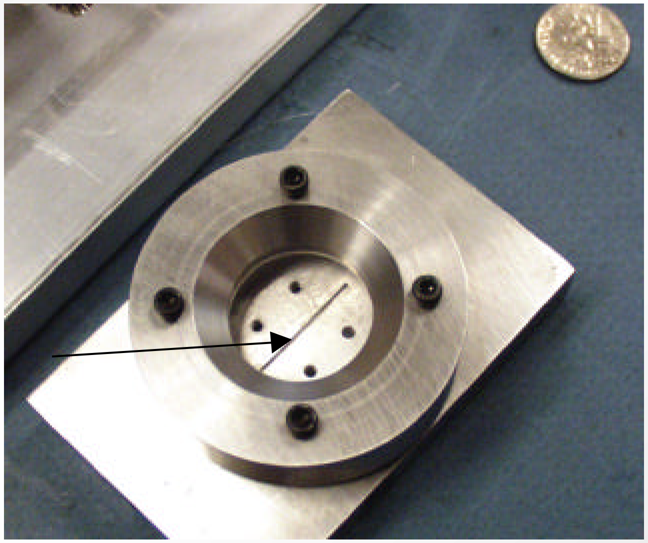
Flame Speed and Pulse Rate

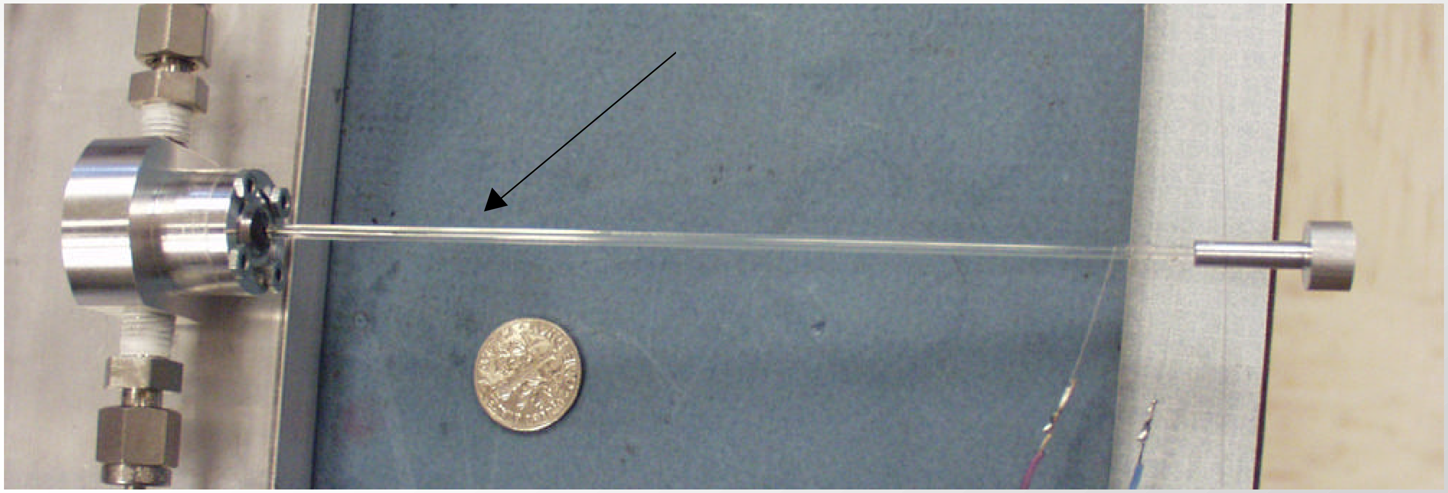




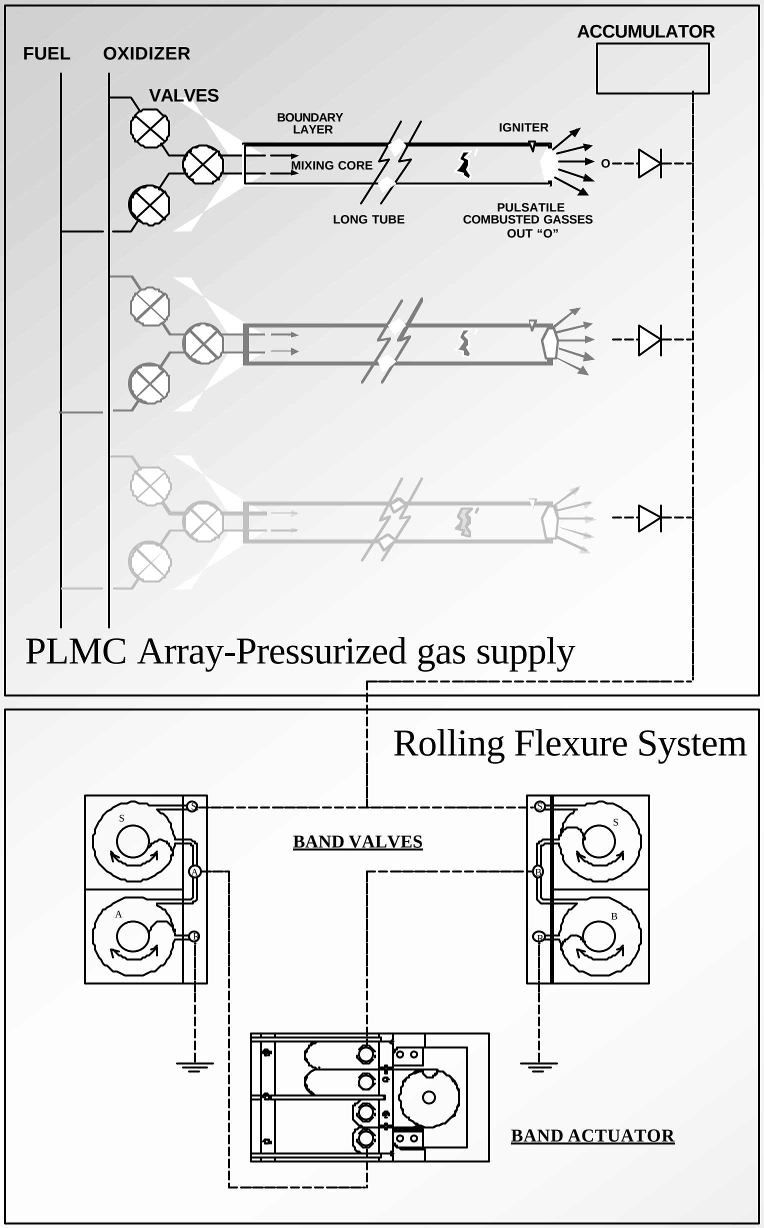
Other PLMC Test Set-ups (2)

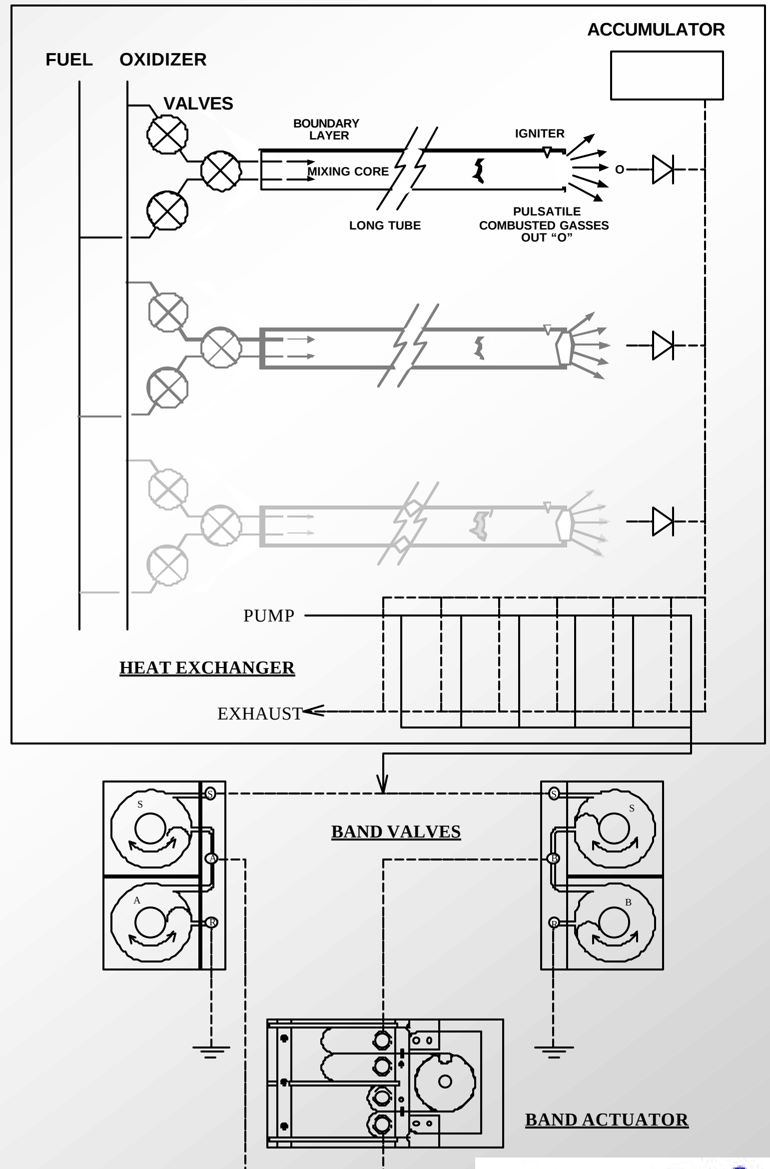

Cylindrical Combustors


Planar - "channel combustor"



PLMC-array Supplies for Rolling Flexure Actuators





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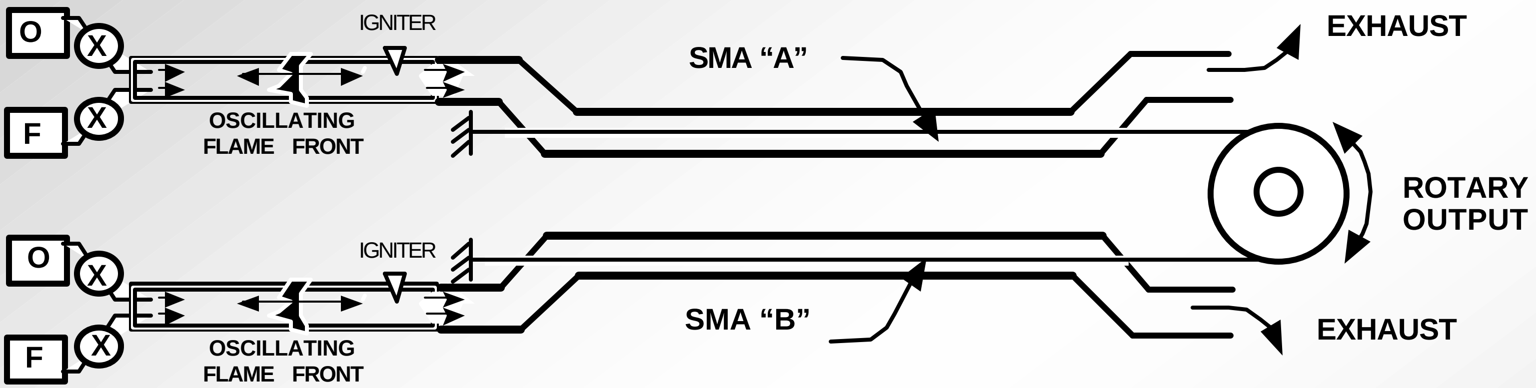
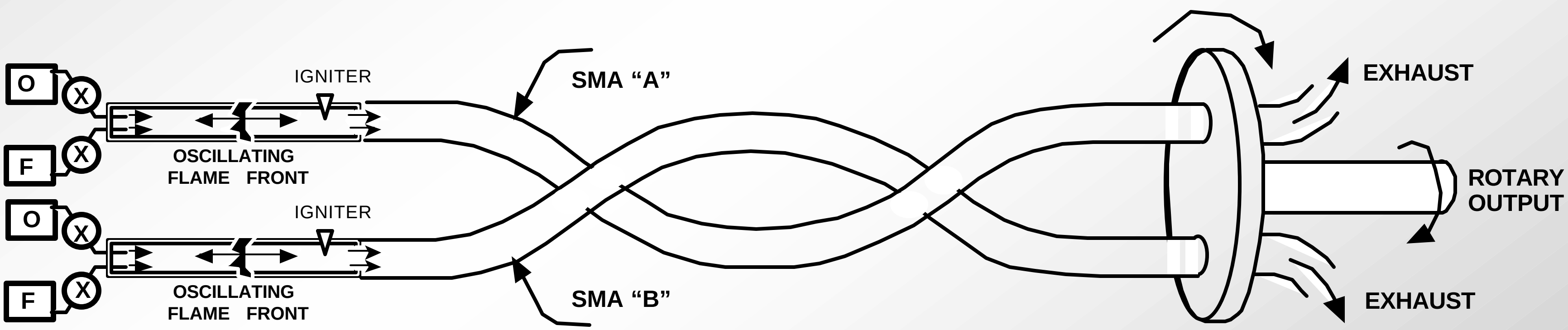
PLMC-driven SMA Actuators





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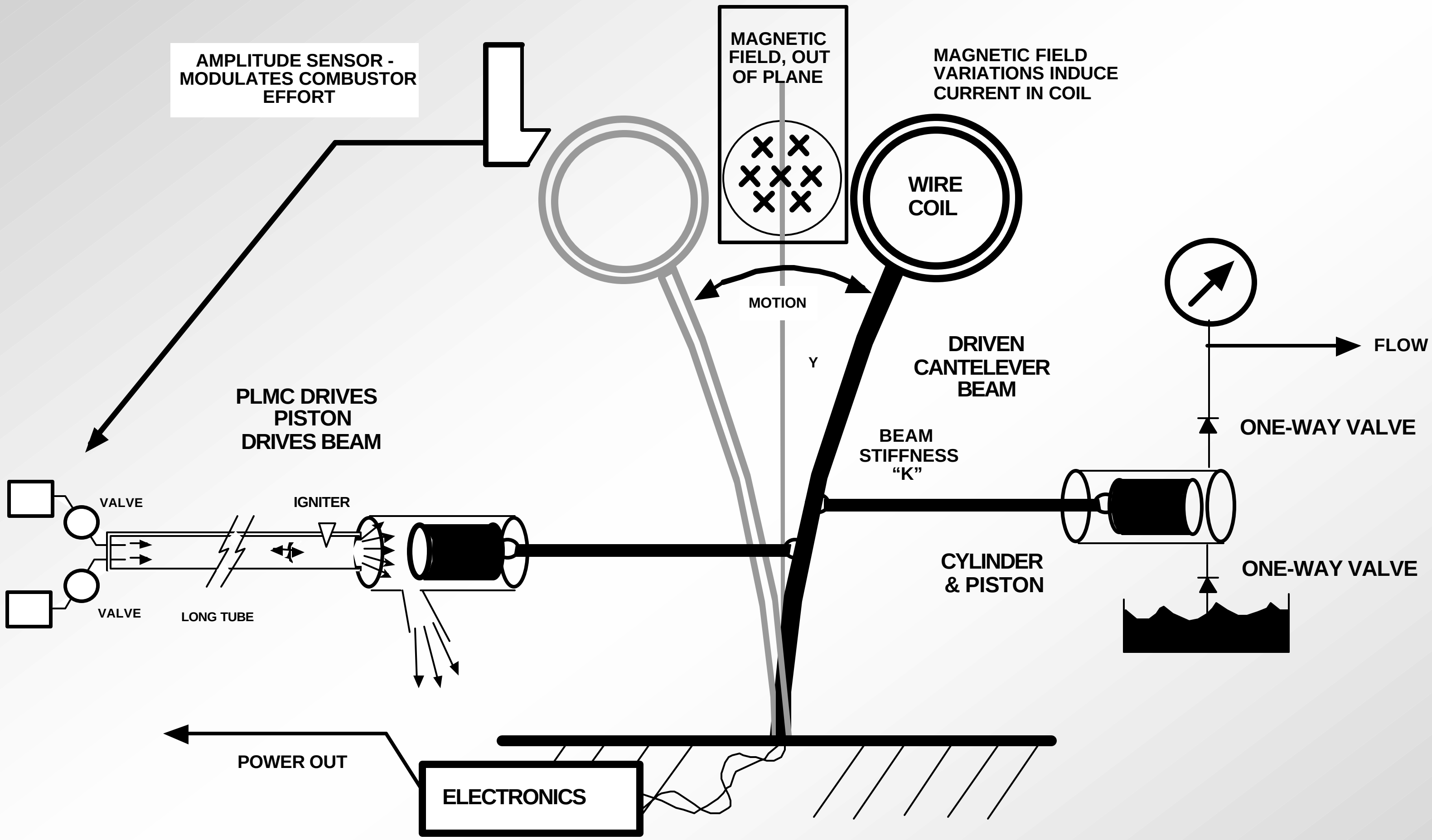
PLMC Driven Resonant Supplies



PLMC and PLMC arrays may be used to drive Resonant Electrical, Pneumatic or Hydraulic Supplies, which may then be combined with energy converters such as piston, and others.

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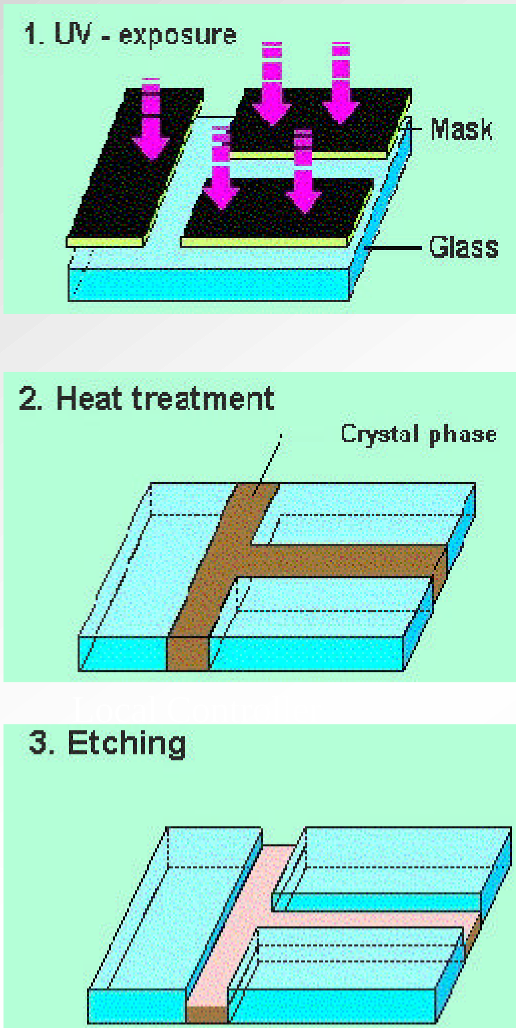
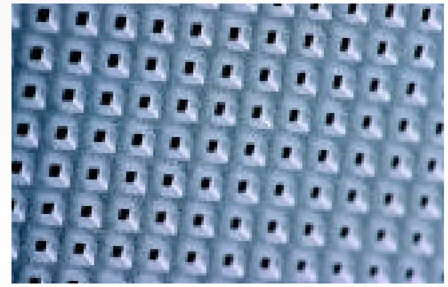
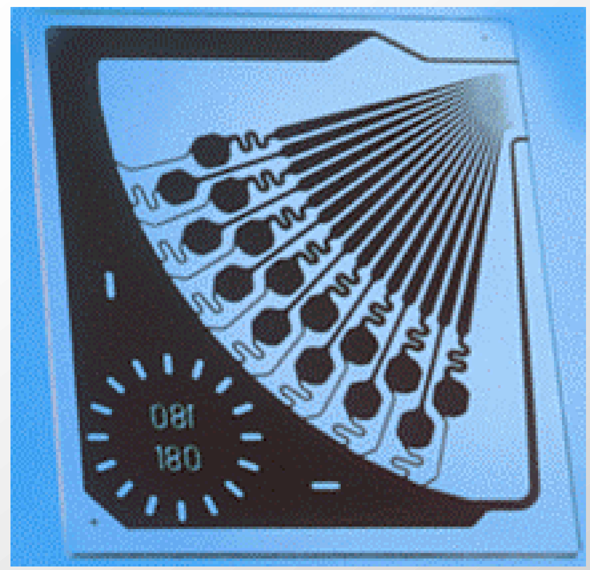
PLMC Fabrication using FOTURAN photosensitive glass

Processing of FOTURAN glass





Array of rectangular holes in FOTURAN (down to 50 µm, in plates up to 2.5 mm thick)



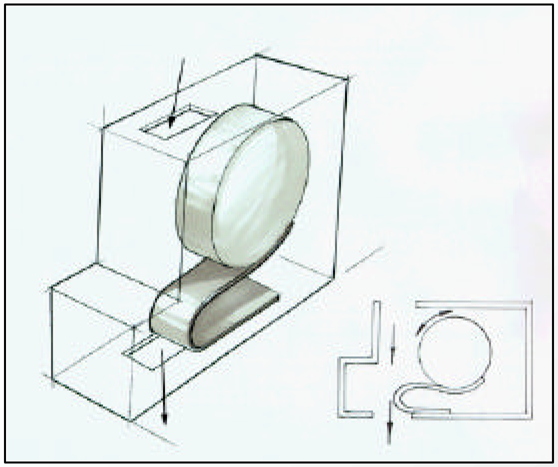
Channels etched in FOTURAN glass

BAND-BASED SYSTEMS

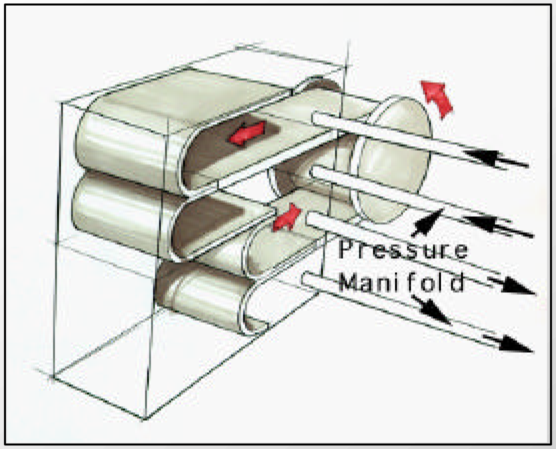
- Band-based Actuators
- Band-based Valve Systems
- Sensor Systems
- Band-based Servo Systems
- Smaller Scale Integrated Band Systems

Rolling Flexure Actuation Systems

- **Rolling Flexure Systems (Valves and Actuators)**
  - » A new approach to build high performance valves and actuators.
  - » Use thin, flexible band (rolling flexure) to modulate fluid flow or to apply force/torque on an external element (e.g. rotary joint).
- **Rolling Flexure Systems have Several Advantages**
  - » Very high throughput (valves) - thereby allowing high force modulation bandwidth in pneumatic systems.
  - » Large bandwidth (rolling flexures have low inertia).
  - » Minimal power consumption for actuation.
  - » Simple packaging.
  - » Robust and Reliable (few moving parts).
  - » Light weight/small size.
  - » Low cost.
  - » Easily integrated in the parent structure.
  - » Approach readily applicable at the macro, meso and micro-scale.

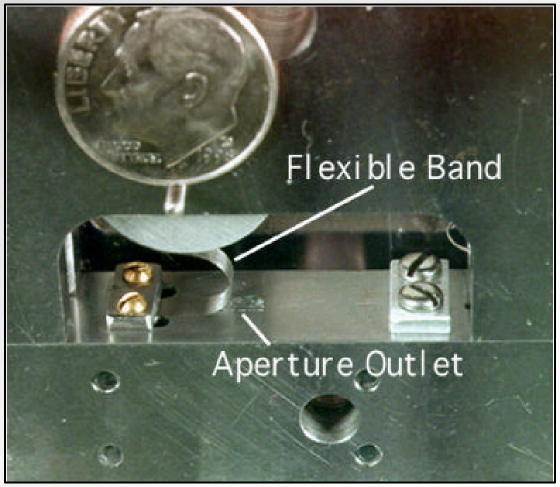


Band Valve - Principle of Operation

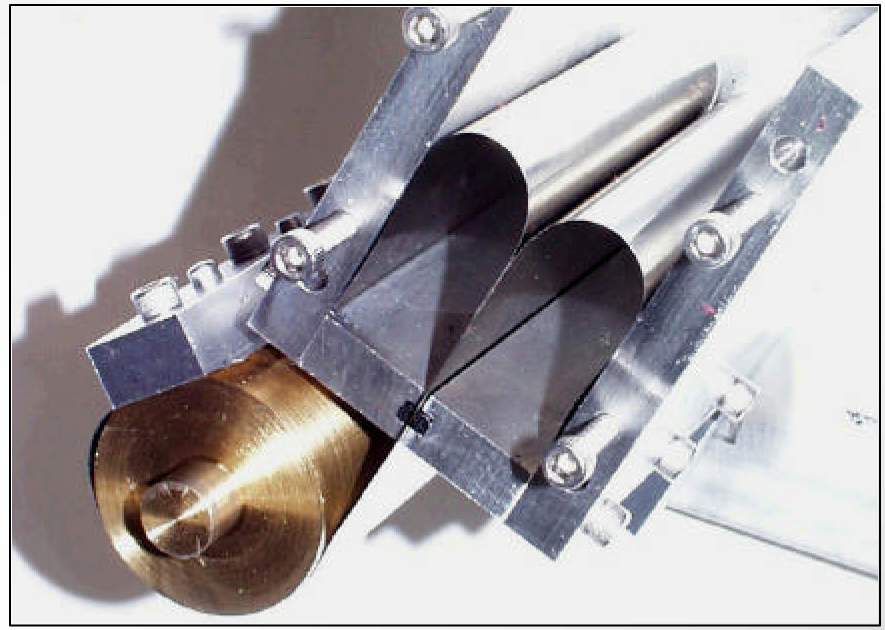


Band Actuator - Principle of Operation

Pneumatic/Hydraulic
"Band Valves and Actuators" - Early prototypes



Band Valve (Hydraulic)



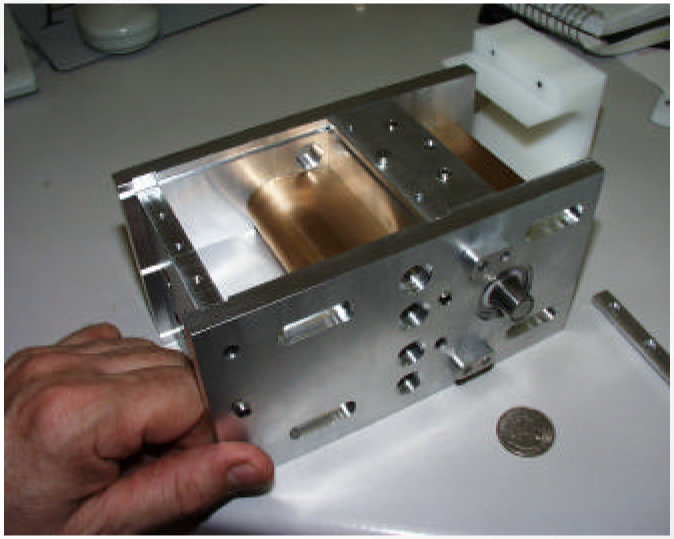
Band Actuator (pneumatic)

Rolling Flexure Actuation System

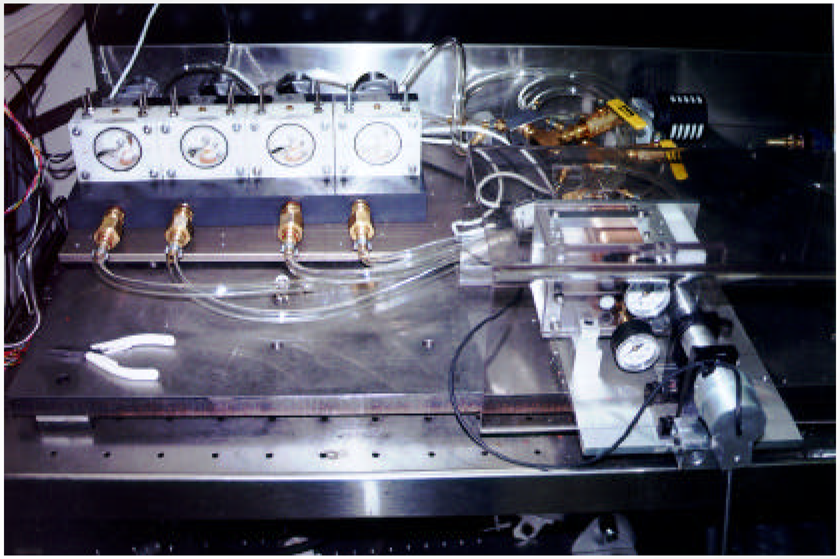
• Test System developed to evaluate performance of hybrid 4-way valve (each valve controlled independently) and Actuator.

• System tested in open and closed-loop

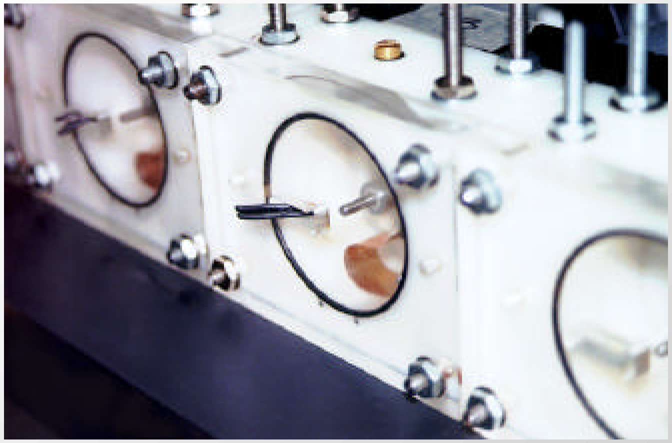
• System also used to evaluate Band Actuator low friction and low leak rate sealing approaches



Band Actuator "Antagonistic Rotary"



Band Valves (4-way) and Band Actuator



Band Valves

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