Direct Energy Conversion Actuators for Ambulatory Robotic Systems

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SBIR Phase I

Presented at DARPA Smart Structures Technology Interchange Meeting

Baltimore, MD -- June 26 - 28, 2000

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Direct Energy Conversion Actuators for Ambulatory Robotic Systems

a) Background

(1) Start Nov. 4, 1999, End July 15, 2000

(2) funds - $99K

b) Objectives

(1) Preliminary Definition of Actuator Requirements for Human-Scale Mobile Robots

(2) Preliminary Characterization of prototype Micro-Combustion module.

(3) Evaluation of candidate Manufacturing Methods that can be adapted for the large scale fabrication and integration of Arrays of Micro-Combustor-based Energy Supplies

(4) Develop Concepts and Analysis of Microcombustion-driven, Direct Energy Conversion Actuators

c) Work Completed

(1) Review Specifications and Requirements for Human Scale Robotic Actuators

(2) Development and Analysis of New Concepts for Combustion-Driven Actuators is currently in progress

- i) Concepts for Integration of Arrays of Pulsatile Micro-Combustors including
  - > Fuel and Oxidizer Buses
  - > Mixers, and Inlet Valves
  - > Combustion Chamber
  - > Outlet Valves
  - > Accumulators or Heat Exchanger

(3) Development of Concepts and Analysis of Pulsatile Micro-Combustion-driven Resonant Micro-Pump (for high performance compact pneumatic supply) is in progress

(4) Evaluation of Performance of Capillary-type Micro-Combustion is in-progress

(5) New methods for the fabrication of Integrated Pulsatile Micro-Combustor Arrays and heat exchangers have been identified and are being evaluated

- i) Very promising method is based on the use of a photolithographically paternable ceramic (Foturan™)

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Direct Energy Conversion Actuators

Work Completed

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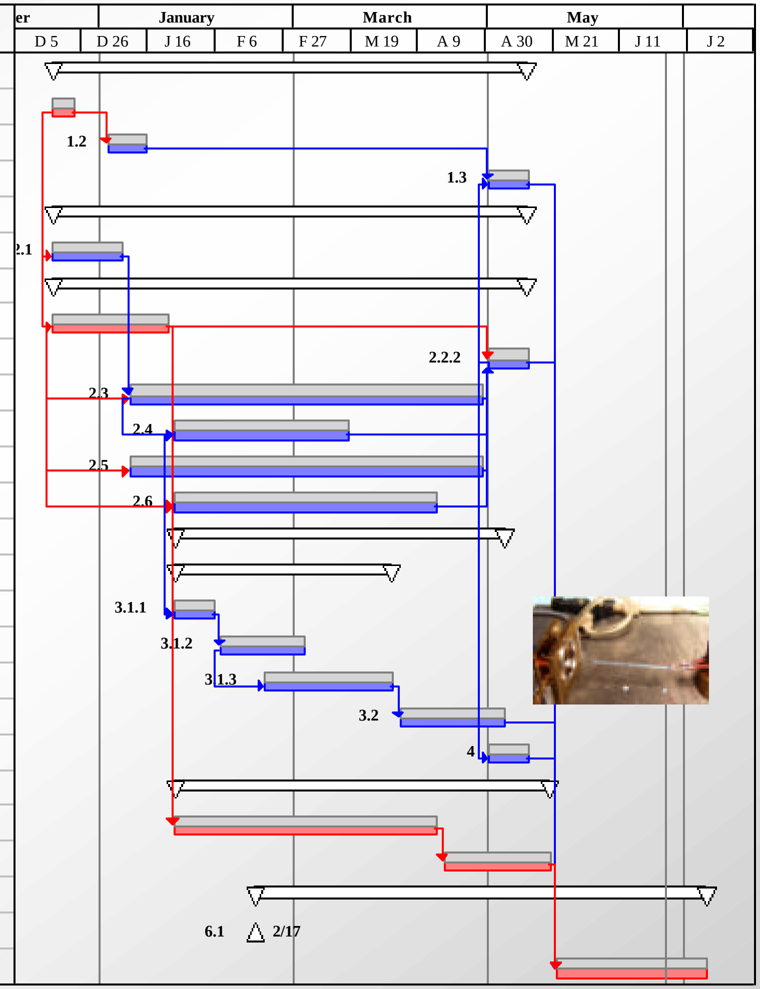
Direct Energy Conversion Actuators for Robotic Applications - Phase I Plan

ID	WBS	Task Name
1	1	**Actuation System Requirements and Specifications**
2	1.1	Draft Requirementfor Human Scale Robot Actuators
3	1.2	Draft Targeted Specs. for Human Scale Robot Actuators
4	1.3	Requirerements/Specs. up-date ("Baseline")
5	2	**Conceptual Design and Analysis Combustion-based Actuation System**
6	2.1	Review of Critical Support Technologies (materials, valves, etc.)
7	2.2	**Develop design concept and anal. at system level**
8	2.2.1	Develop Prelim. System Concepts (incl. fuel supply, integrated actuators...)
9	2.2.2	Up-date System Level Concept Drawing and Analysis
10	2.3	Develop design concepts for key subsystems (fuel mixer, valves, combustor...)
11	2.4	Micro-combustor simulation and performance analysis (A. Sarofim/REI)
12	2.5	Develop design concepts for mechanical actuator (interfaced to combustors)
13	2.6	Develop and anal. integrated sensor and controller concepts.
14	3	**Characterization of Combustion Driven Actuator Critical Tech.**
15	3.1	**Preliminary characterization of single combustion cell**
16	3.1.1	Develop Combustion Cell Characterization Test Plan/Matrix (use REI)
17	3.1.2	Procure/Fab. Test equip. and set-up
18	3.1.3	Characterize combustion cell key param. (temp, freq., conv. efficiency, etc.)
19	3.2	Integration and characterization of combustion cells key element (TBD)
20	4	Critical evaluation of System applications
21	5	**Develop Manufacturing Plan**
22	5.1	Review possible manufacturation techniques
23	5.2	Prepare trade-off/cost analysis of manufacturation methods
24	6	**DECA Phase I QTR and Final Report**
25	6.1	QTR Report 1
26	6.2	DECA Final Report



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Energy Storage and Power Modulation for Autonomous Robotic Systems

Energy Storage and Power Modulation for Actuation

i) New Combustion-based Actuation Systems

> micro combustion and other approaches

> new concepts based on meso, micro

> Rolling Flexure Actuators (RFA)

ii) Power Modulators

> optimally recruited elements to produce servo-controlled actuation without the use of inefficient throttling processes. Examples of current inefficient approaches include:

* in fluid systems, variable resistors to adjust pressure
* in electrical system, variable time or loss to adjust voltage

iii) The focus for the DECA Project - Energy Storage and Conversion

> Micro-Combustion

> **Resonant Systems (MicroCombustion-driven Pumps)**

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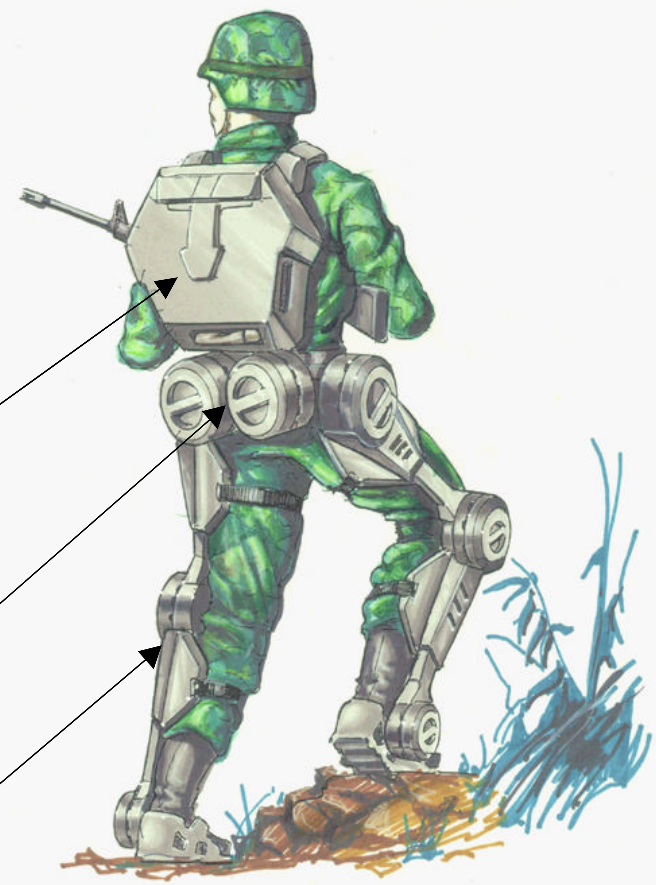
Example Application for DECA

- 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

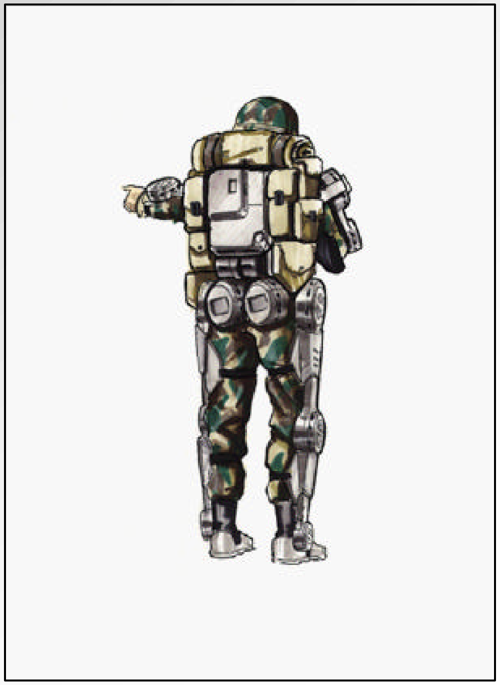
Legs (8 DOF)



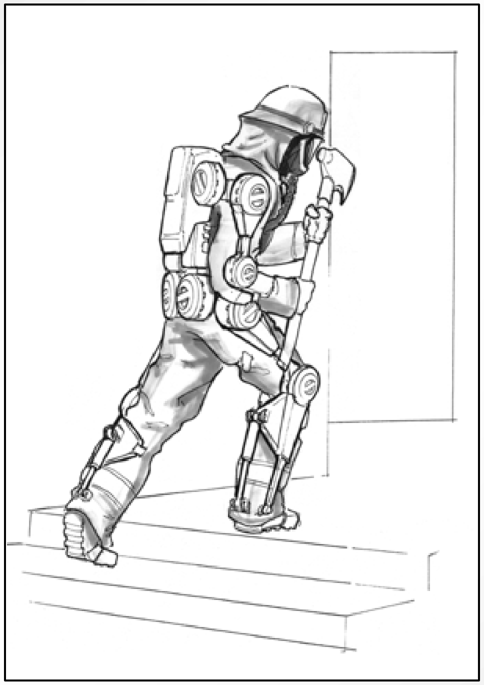
Exoskeleton Base Unit

EHPA Application Specific Packages (II)

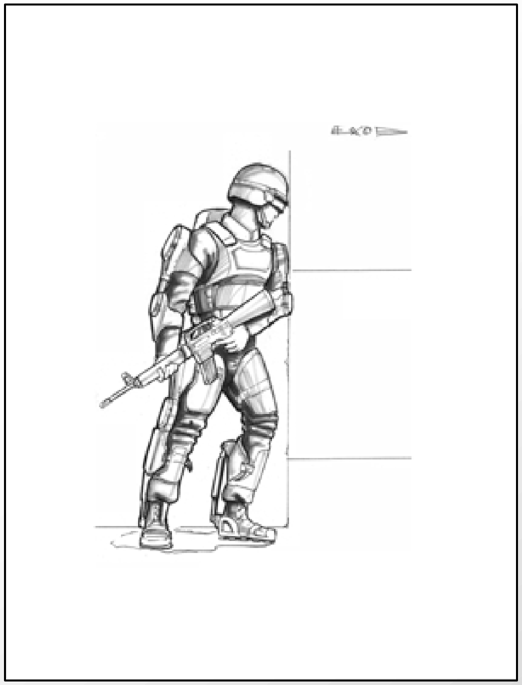
Applications of Untethered EHPA



Soldier Mule



Fire/Chemical Protective suit



Body Armor

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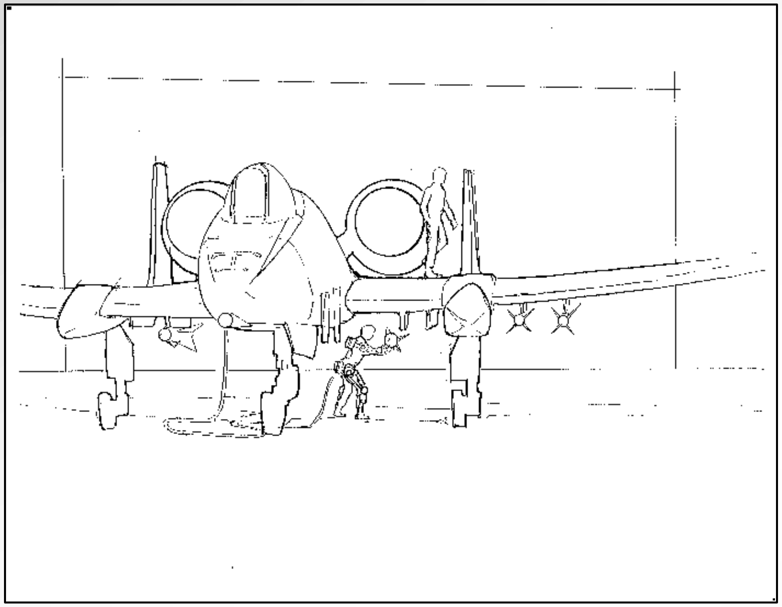
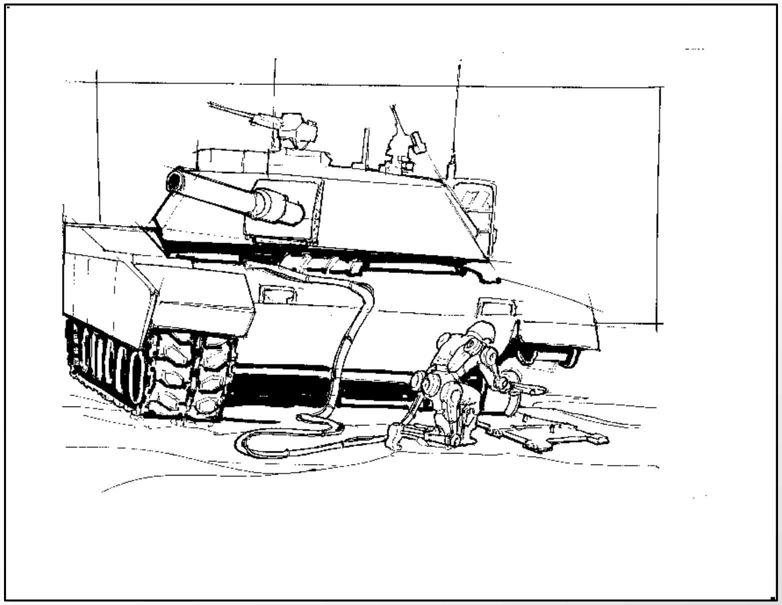
EHPA Application Specific Packages (I)

Applications of Tethered EHPA - High Strength



Aircraft-tethered EHPA used for Munitions Handling



Tank-tethered EHPA providing strength required to change damaged track

Problems with Actuators

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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Important Actuator Properties

ACTUATOR PROPERTIES

PERFORMANCE, RELIABILITY & ECONOMY

INPUT -
- **VOLTAGE,PRESSURE**
- **CURRENT,FLOW**

REDUCTION

SIZE WEIGHT

COST, LIFE

STICTION BACKLASH

IMPEDANCE -
- **DAMPING, STIFFNESS**
- **INERTIA**

EFFICIENCY -
- **LOSSES, LEAKAGE**

THERMAL TOLERANCE

LIFE -
- **RELIABILITY,**
- **ABUSE TOLERANCE**

THERMAL

SUPPORT SYSTEMS REQUIRED

EMISSIONS -
- **SOUND, VIBRATION,**
- **THERMAL, RADIATION**

RESOLUTION

AND MORE !

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PULSATILE LINEAR MICRO COMBUSTORS (PLMC)

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

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

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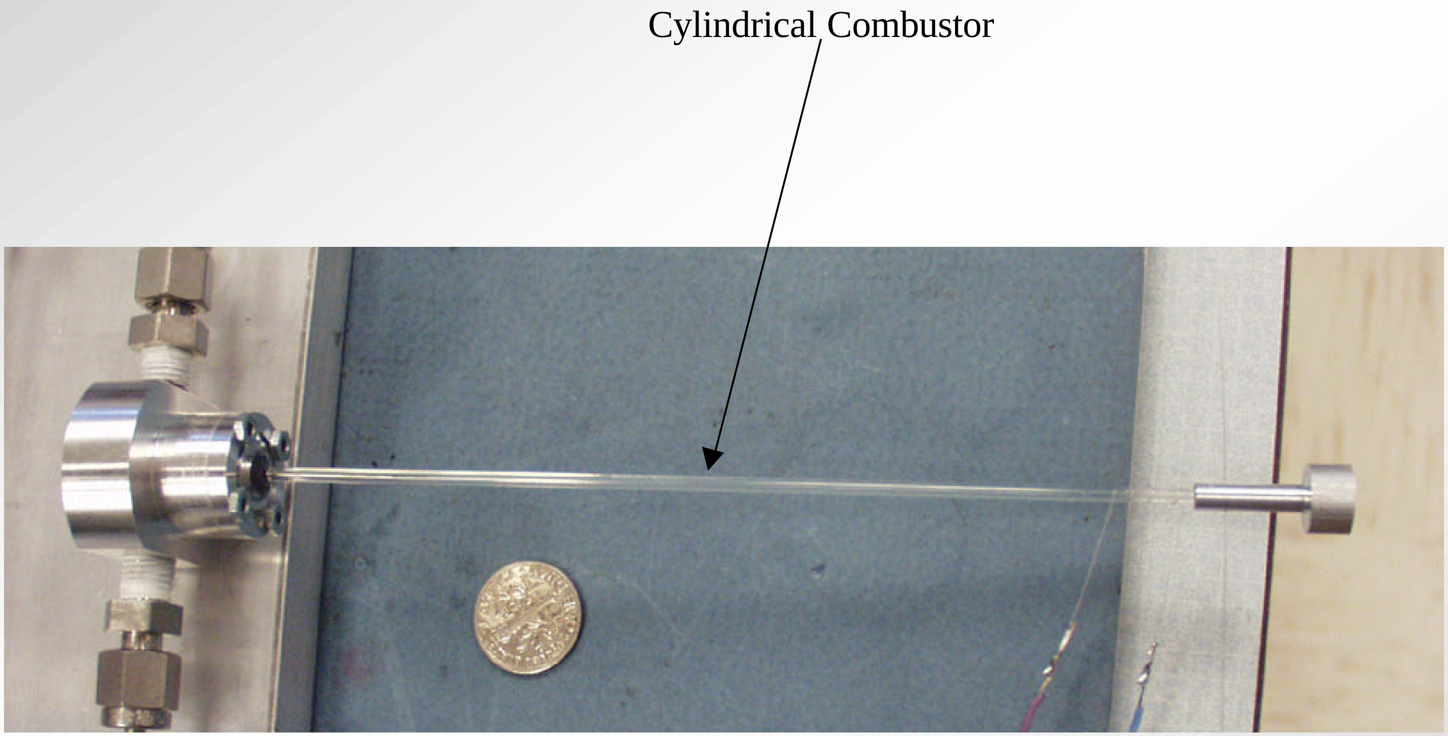
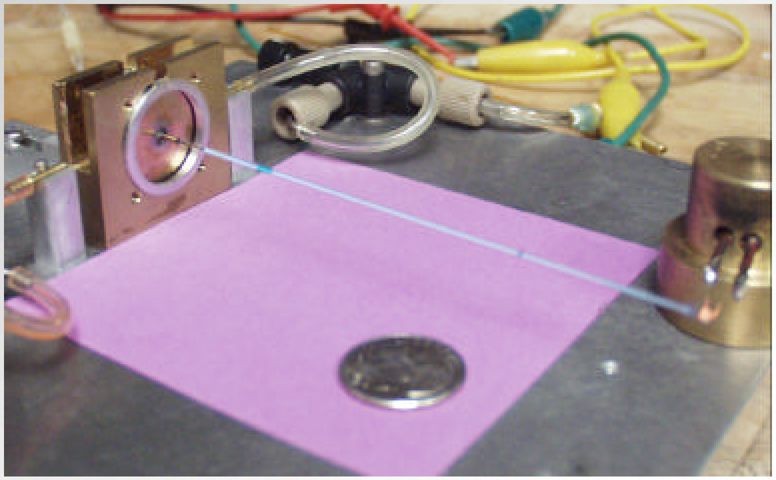
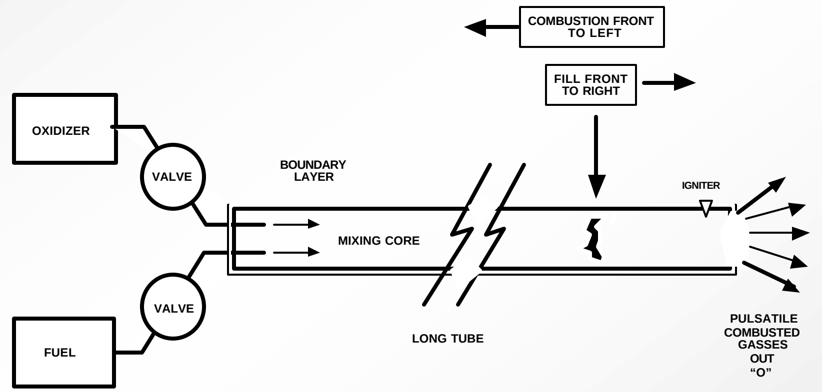
PLMC Test Set-up



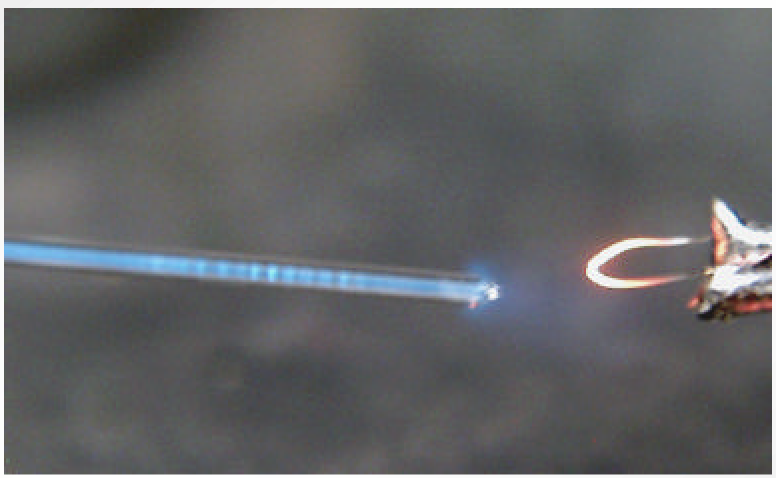
PLMC Principle of operation and Test Set-ups



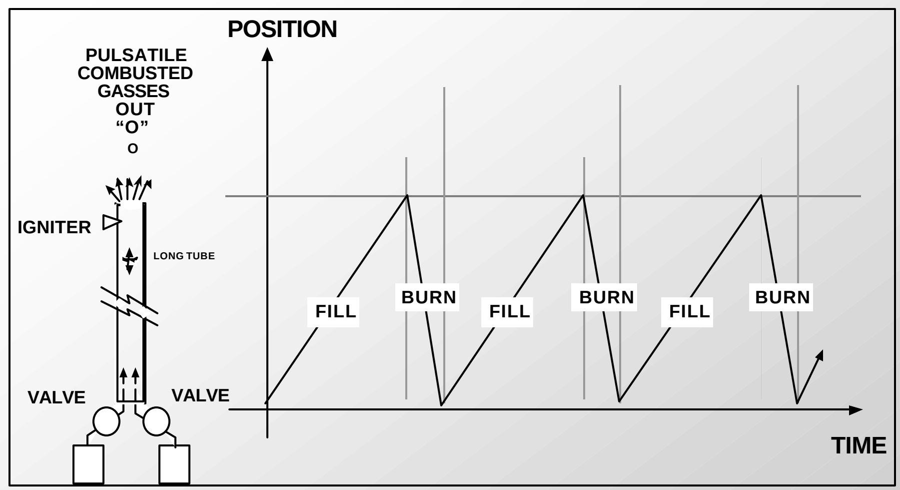
PLMC Test Set-up (1)



Schematic Representation of a PLMC

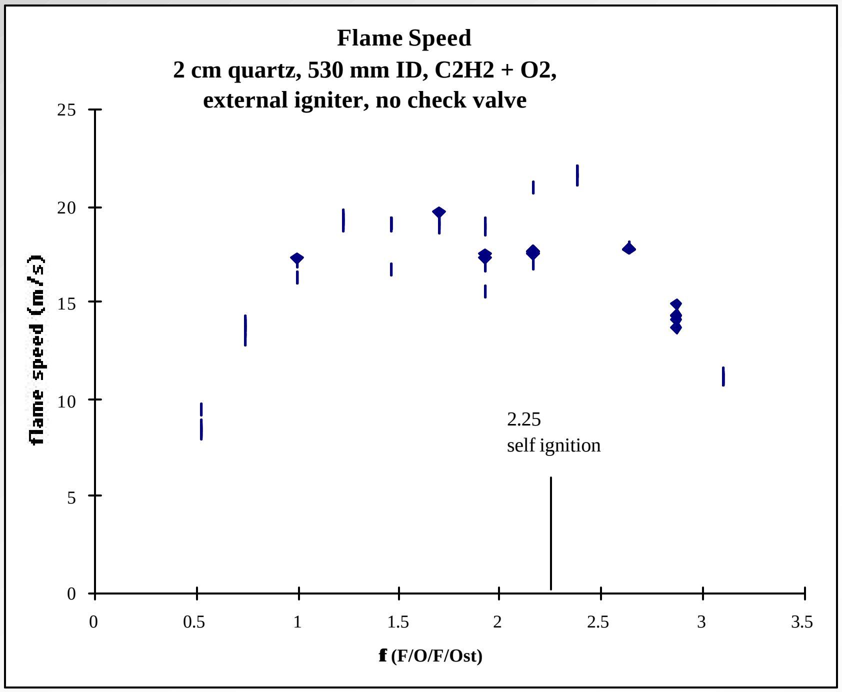


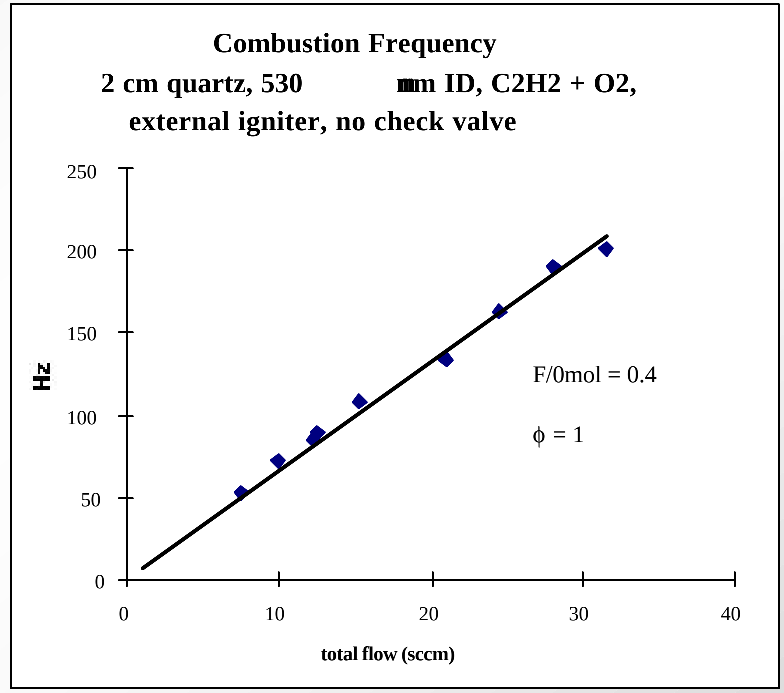
Flame Propagation in PLMC



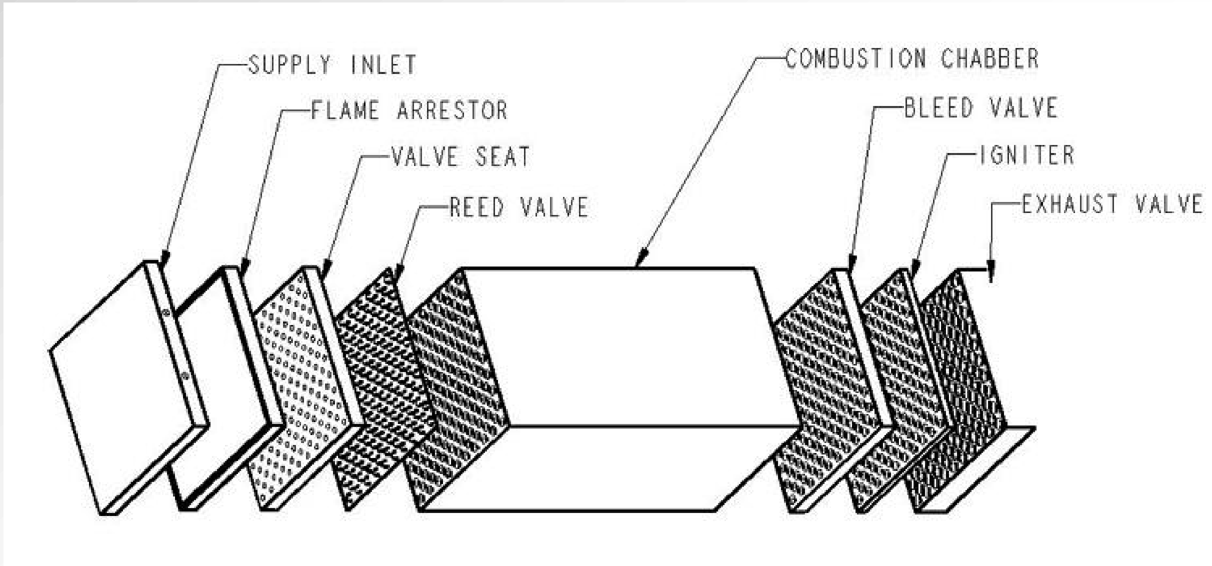
Typical Fill/Burn cycle in PLMC

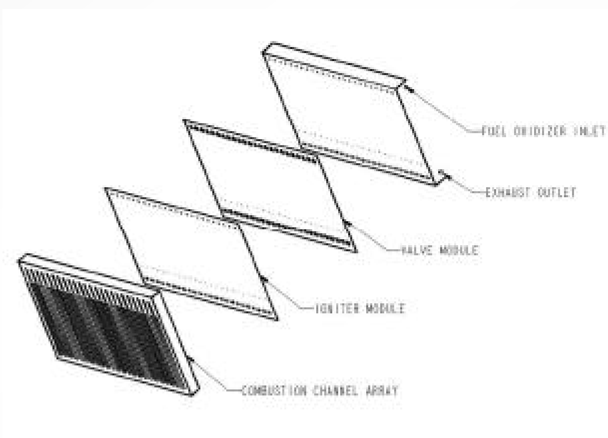
Flame Speed and Pulse Rate

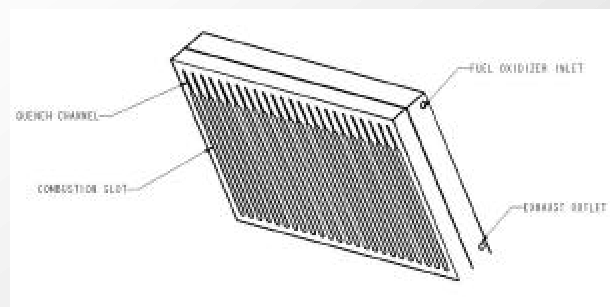




Longitudinal and Stacked Combustor Packaging Approaches







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RESONANT MICRO PUMP

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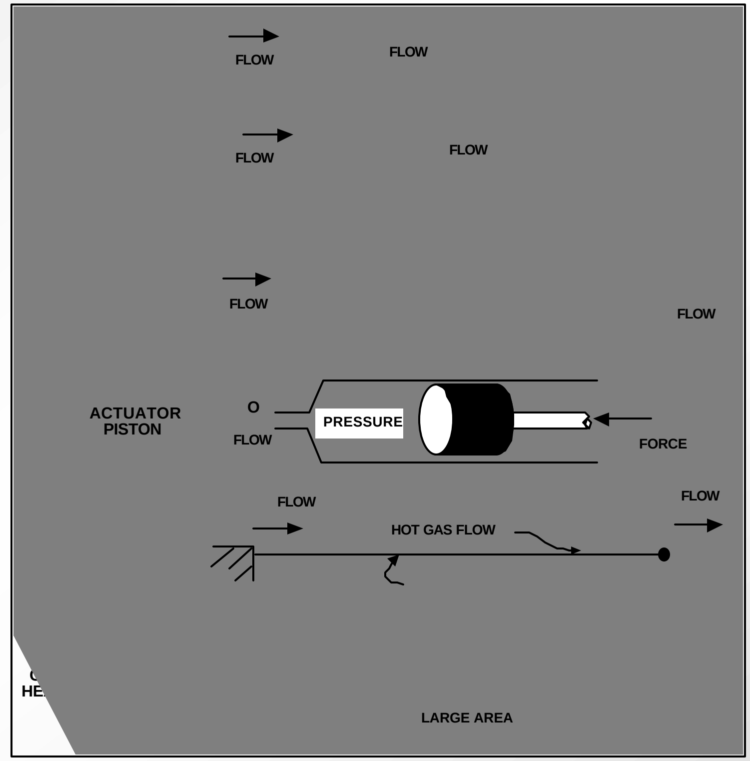
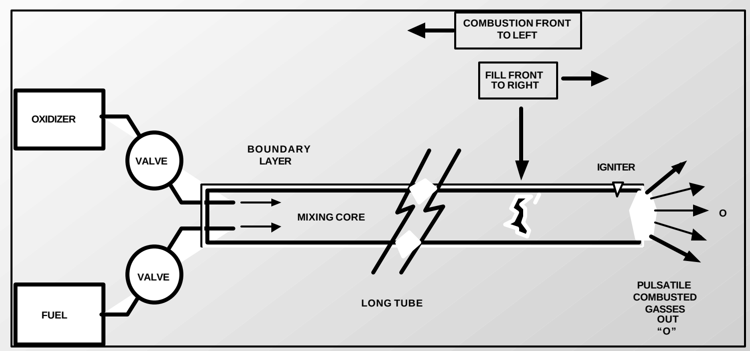
Micro-Combustion-based Energy Supplies

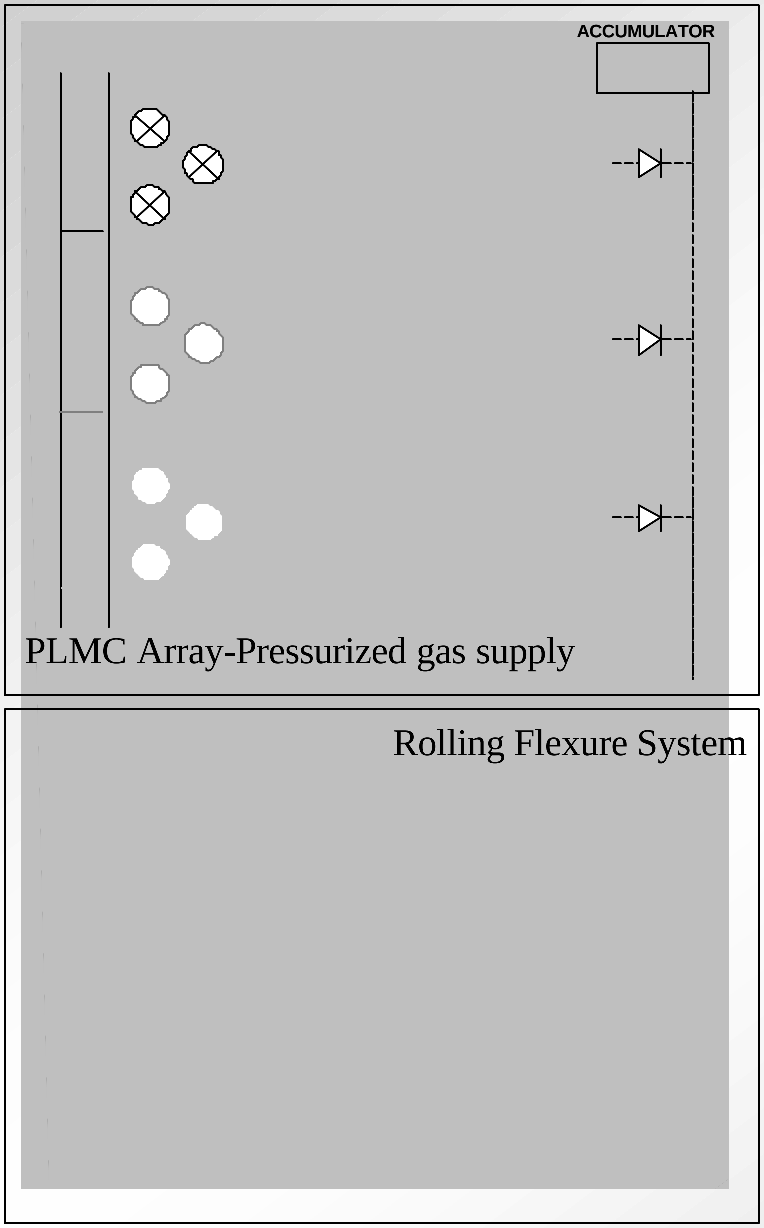
New compact energy supplies for Energetically Autonomous Systems

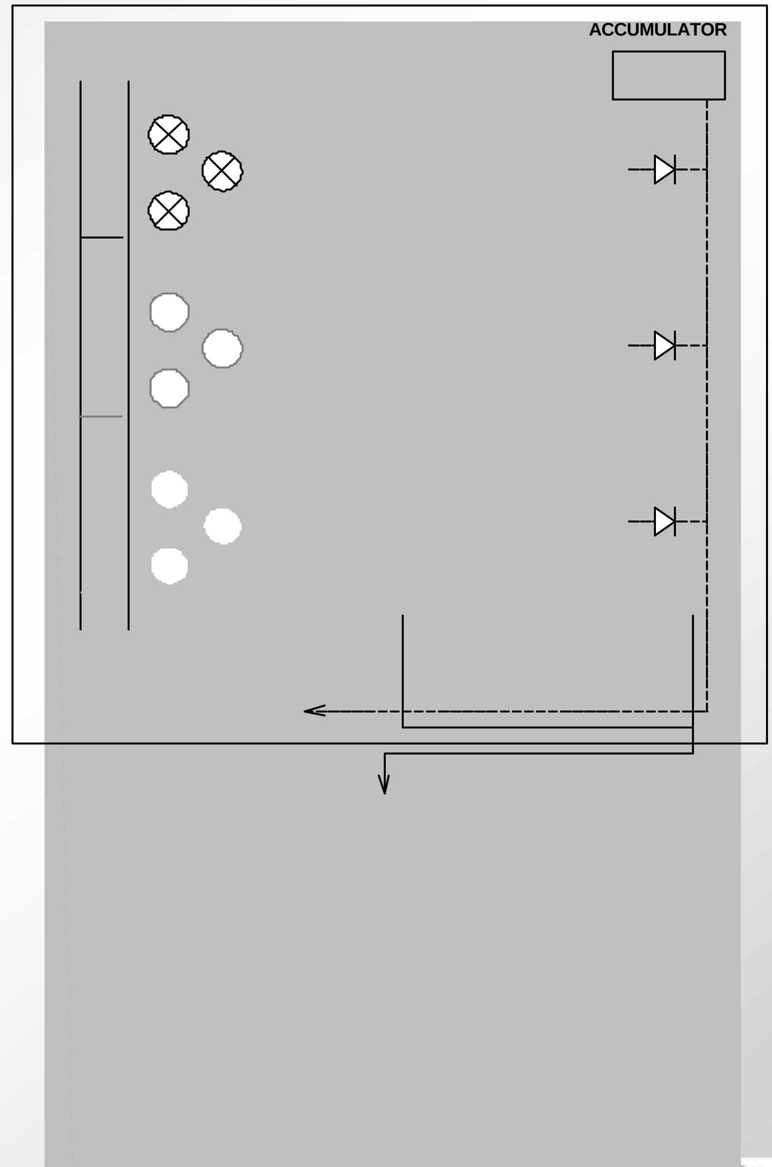
- New approach is similar in architecture to biological systems
- Energy supplies are built around arrays of Pulsatile Linear MicroCombustors (PLMC)
- Individual PLMC designed to operate at optimal efficiency in an oscillatory mode
- Controlled Proportional Output achieved by recruiting PLMCs as a function 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.



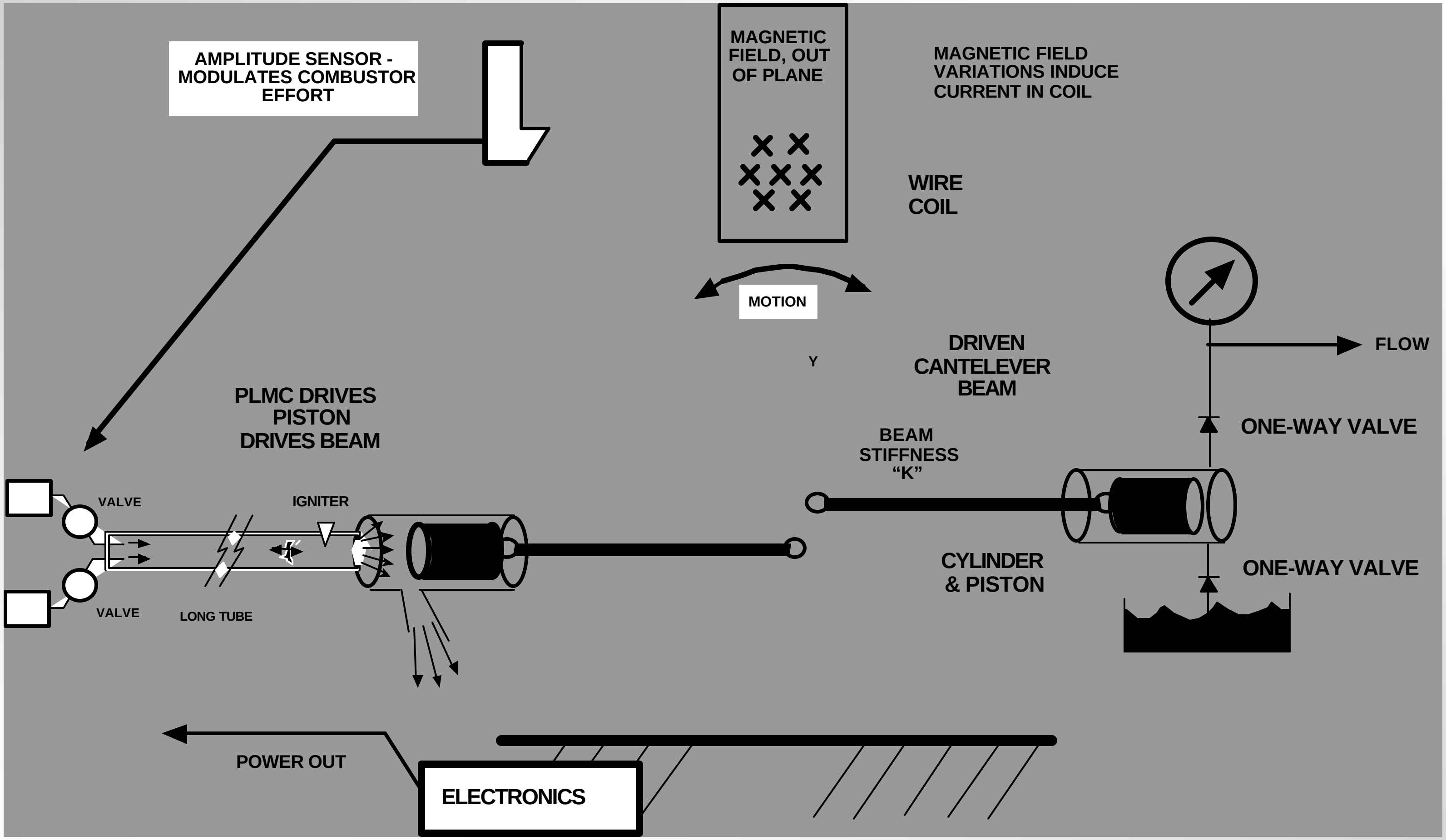


PLMC-array Supplies for Rolling Flexure Actuators



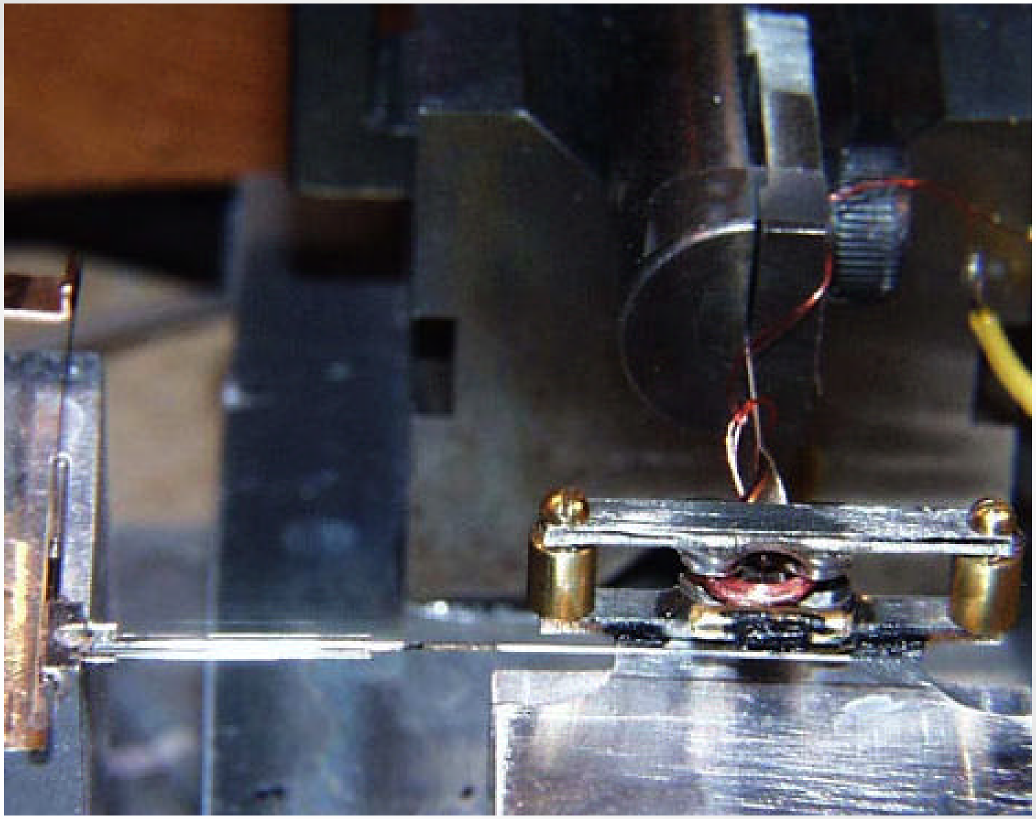


PLMC Driven Resonant Supplies



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.

ELECTRICALLY DRIVEN RESONANT MICRO PUMP



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NON PLANAR MICROFABRICATION APPROACHES

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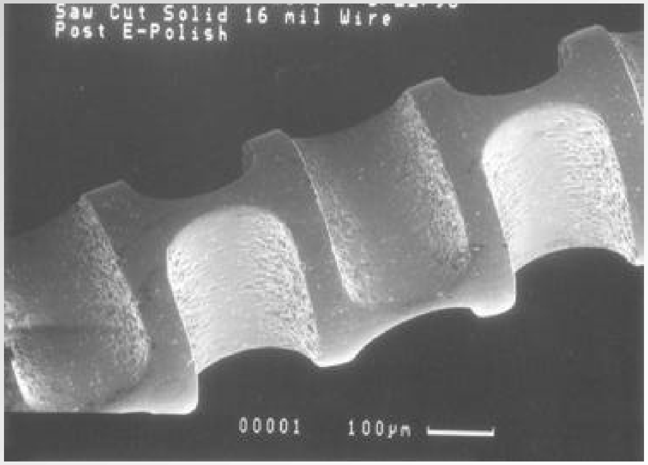
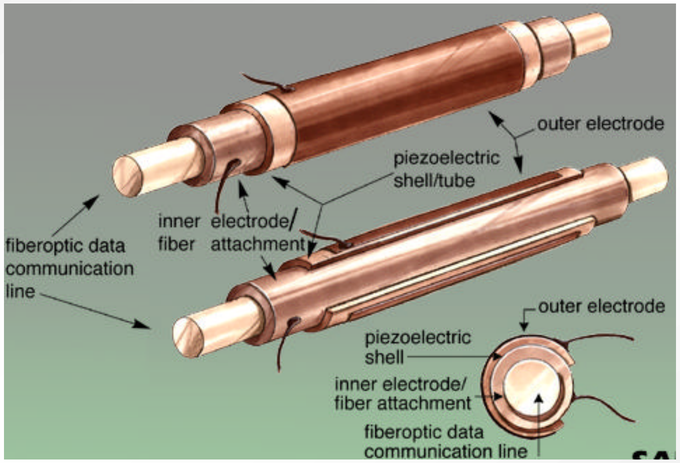
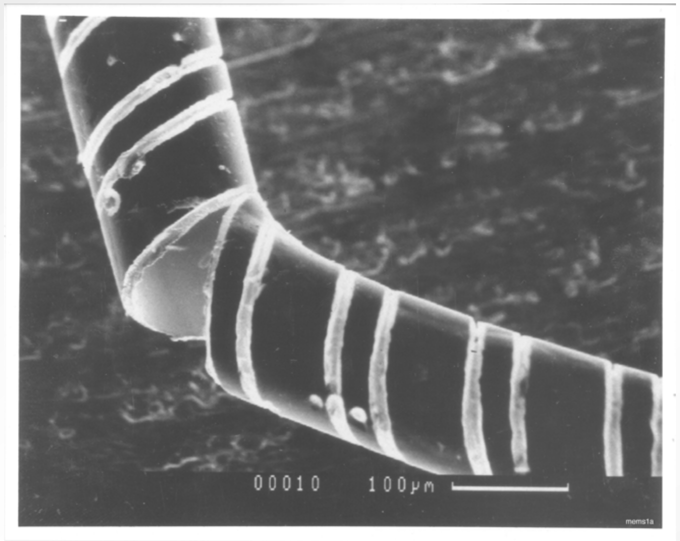
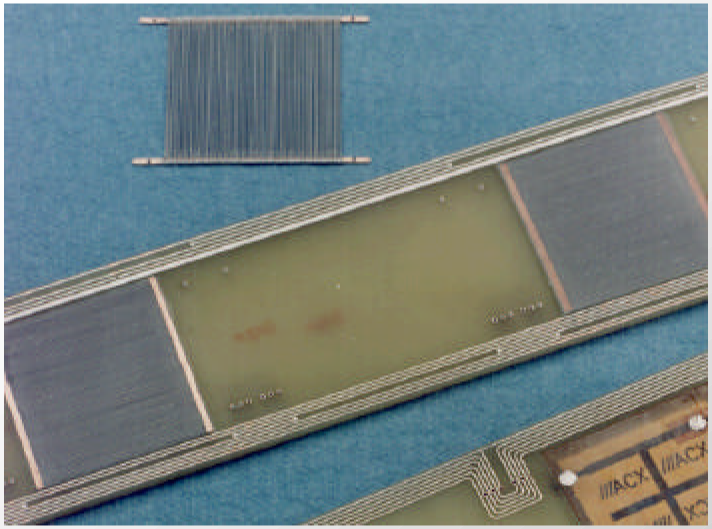
Cylindrical Micro-Fabrication









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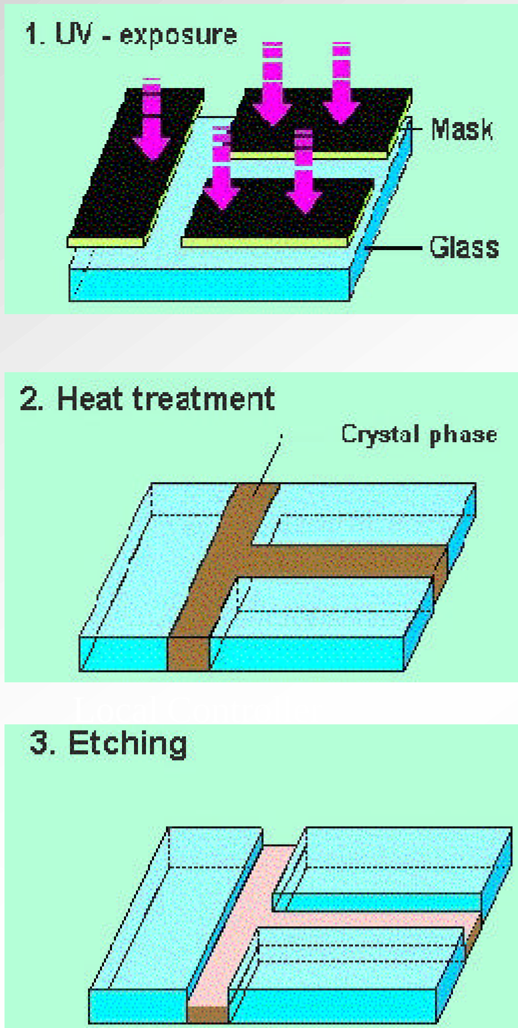
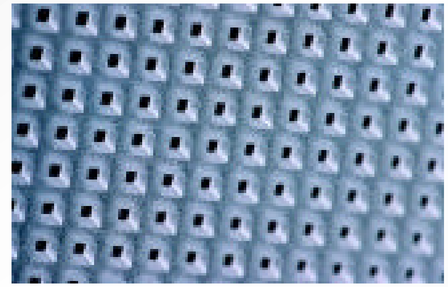
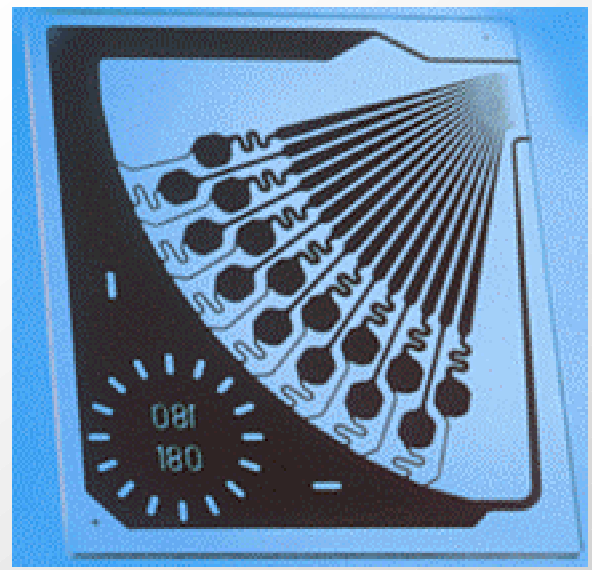
PLMC Fabrication using FOTURAN photosensitive glass

Processing of FOTURAN glass





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

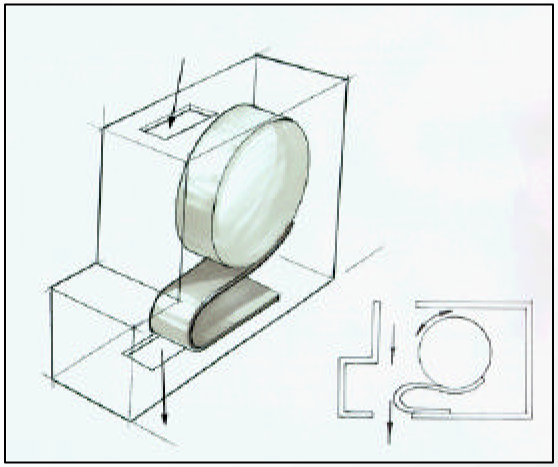


Channels etched in FOTURAN glass

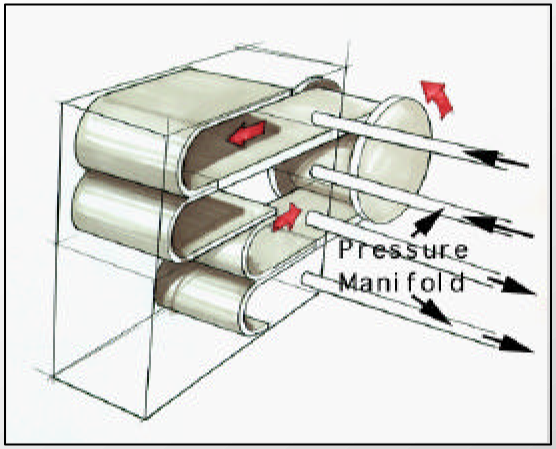
BAND BASED SYSTEMS

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

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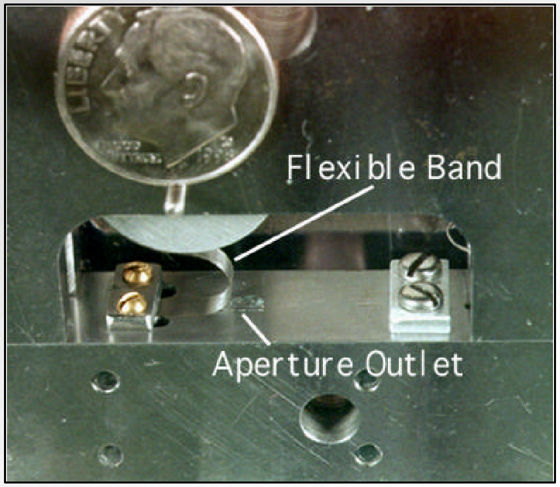
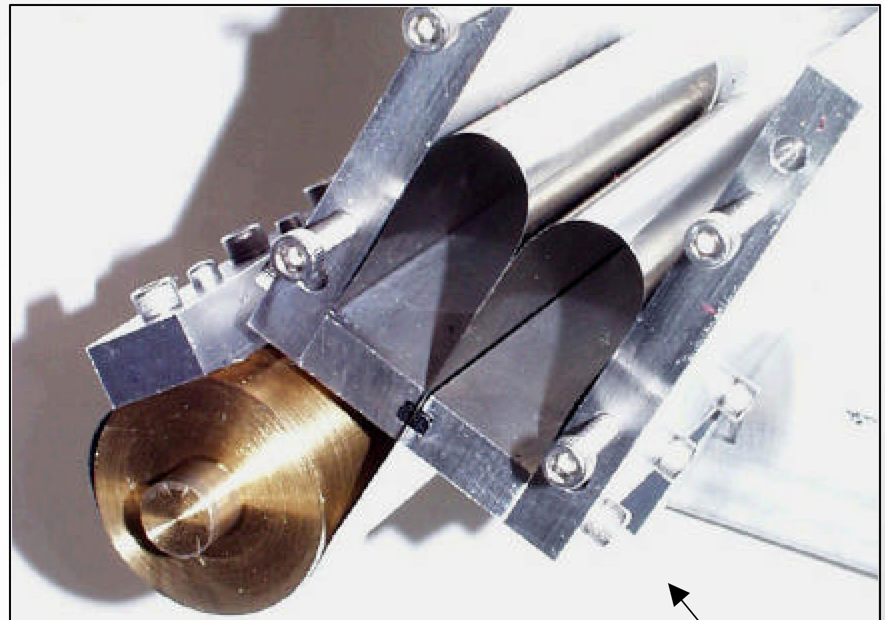
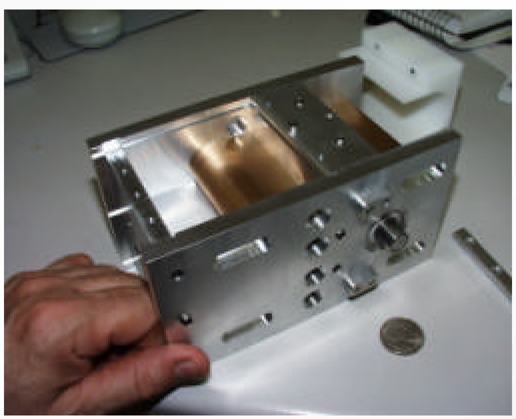
Pneumatic/Hydraulic
"Band Valves and Actuators" - Early prototypes



Band Valve (Hydraulic)

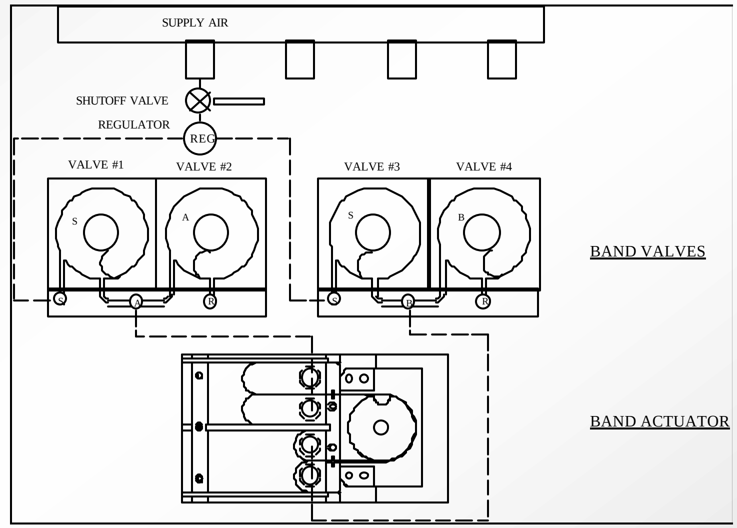




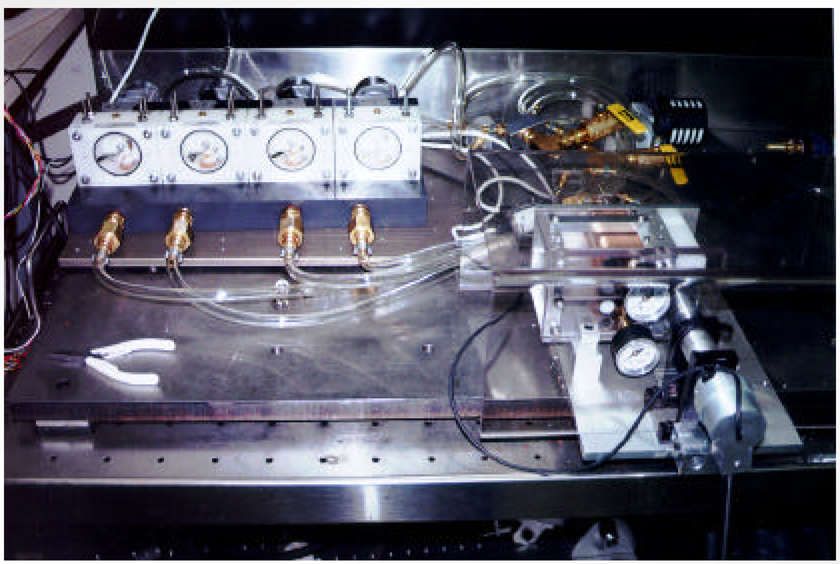
Band Actuator (pneumatic)

Rolling Flexure Actuation System

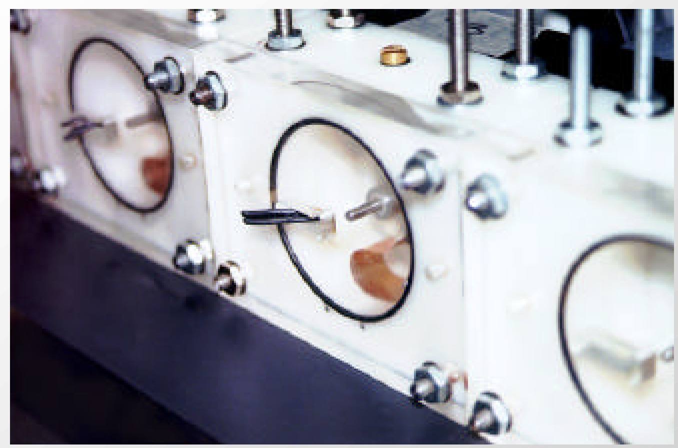
- Test System developed to evaluate performance of hybrid 4-way valve (each valve controlled independently) and Actuator.
- System tested in open and closed-loop
- System also used to evaluate Band Actuator low friction and low leak rate sealing approaches



Band Actuator "Antagonistic Rotary"



Band Valves (4-way) and Band Actuator



Band Valves

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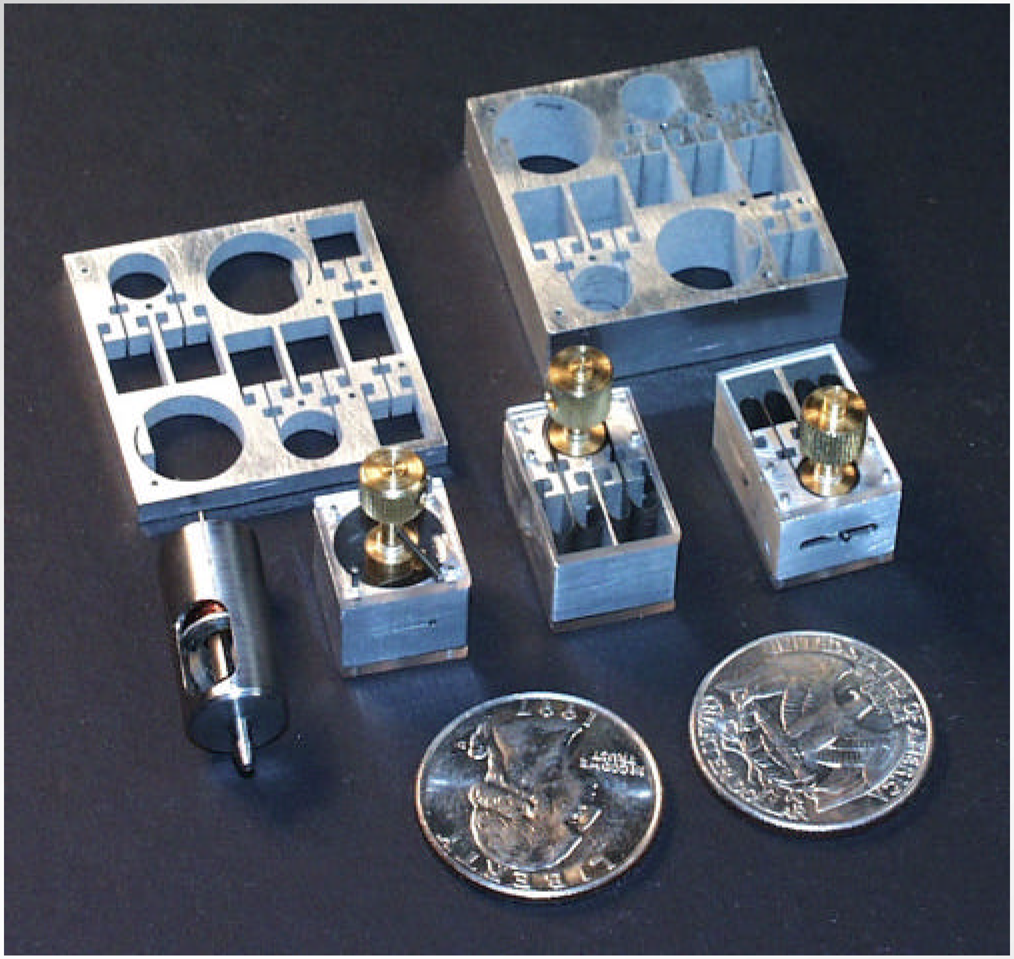
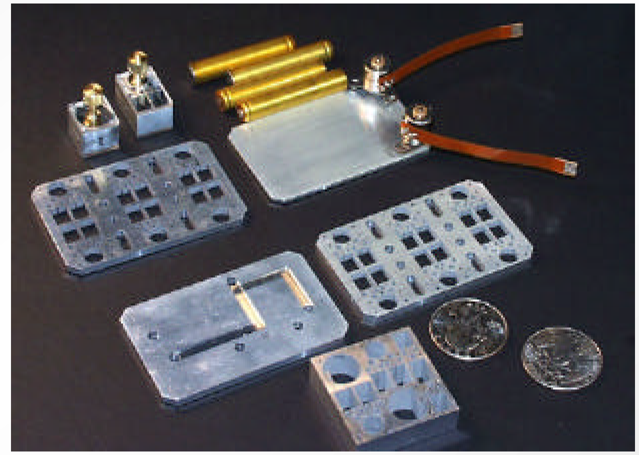
“Meso-scale” Integrated Rolling Flexure Systems



Components of Integrated Rolling Flexure Actuators and examples of “Antagonistic and Rotary” Joint actuators



Components showing how multiple actuators may be integrated in a structure

Rolling Flexure Systems can readily be built into structures, thereby providing for very efficient/compact packaging of Actuators, Valves, Sensors and working fluid (gas or liquid) routing.

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WORK COMPLETED - DECA

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