NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CONTRACT **NO. NAS 7-918**

TECHNICAL SUPPORT PACKAGE

On

DEVELOPMENT OF SMALL, MOBILE, SPECIAL-PURPOSE ROBOTS

for March **98**

NASA TECH BRIEF Vol. 22, No. 2, Item #109

from

JPL NEW TECHNOLOGY REPORT NPO-20267

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JPL Technology Reporting Office

pp. i, 1-15

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March 98

Development of Small, Mobile, Special-Purpose Robots

A report presents a scenario for the proposed development of insectlike robots that would be equipped with microsensors and/or micromanipulators, and would be designed, variously, to crawl, burrow, swim, fly, or hop, to perform specific tasks in fields as diverse as exploration, micropositioning, and surgery. In part, the report reiterates and extends previous discussions of this concept from a number of previous *NASA Tech Briefs* articles and supporting documents, including those mentioned in the immediately preceding article. One notable feature not mentioned previously is a proposed hierarchical scheme in which insectlike exploratory robots would communicate with fewer larger, more-complex robots, and so forth up a hierarchy to a central robot or instrumentation system. The report discusses the historical background of the concept, presents an overview of the uses and functions of the robots, describes the objective and justification for a program of research and development, and summarizes the potential technological and economic advantages offered by the proposed robots. The report goes on to discuss the advanced fabrication, actuator, computer, sensing, computing and power-supply technology that must be developed and refined to implement insectlike mobility and functionality for various robotic tasks. A list of tentative development goals is presented; the final goal in this list is the demonstration of an insectlike exploratory robot in the year 2001 and beyond.

This work was done by Sarita Thakoor of Caltech for **NASA's Jet Propulsion Laboratory**.
NPO-20267

INSECT-EXPLORER TECHNOLOGY DEVELOPMENT: EXPLORATION OF NEW/HAZARDOUS TERRITORY

PROPOSAL DRAFT
Prepared By
Sarita Thakoor

1A. BACKGROUND: Gnat Robots were envisioned in 1987 by Brooks and Flynn. This proposed vision has emerged as a result of spawning of some of those ideas in the mind of a microdevice technologist and thin films engineer. Enclosed is vision of the whole scenario on one hand and the components- how to make them using microdevice technology and materials innovations on the other end.

1B. VISION: The vision consists of generating a new family/class of nanorobotic exploring vehicles, the size of small insects, with the same mobility, agility: and coupled with dedicated microsensors and microimagers. The intent is to mimick biology and produce artificial insects, that possess varied mobility modes allowing both surface/subsurface exploration and atmospheric exploration. THIS NEW BREED OF ARTIFICIAL INSECTS IS VERSATILE IN ITS ABILITY TO CRAWL ON THE SURFACE, CREEP/BURROW THROUGH WIDE CRACKS/ CREVICES TO EXPLORE THE SUBSURFACE NON-INVASIVELY AND IS ALSO FLIGHT AMENABLE DUE TO ITS LIGHT WEIGHT. These artificial insects based on their mobility mode will be built in different varieties such as the surface Roving type, the Hopping type, the Burrowing type, the Flying type etc, each suited to a specific dedicated function determined by the mobility mechanism that it excels in and the specific sensing payload that it carries. These insect explorers would either be remote controlled or self contained solar powered tiny robots that combine the functions of mobility and sensing. These will be batch producible, expendible, dedicated insect explorers that will be programmed for a specific function, e.g. to serve as beacon robots that could be spread around in the exploration zone and will communicate to the lander/microrover/nanorover the sensed information when they find the respective entity that they are tailored for sensing. Therefore essentially no uplink to such solar/compact battery powered self contained explorers will be required, only downlink (wireless RF/optical communication) to get the exploration information will be utilized, thus minimizing on the bulk & size of the explorer and enhancing its manouverability. The heirarchical organisation envisioned is illustrated in figure 1. All three levels of exploration aerial, surface, and subsurface are concieved with multiple species of insect explorers. Each variety of the insect explorer communicates with its nearest hierarchically bigger version ie. insect flyer/hopper downlinks/communicates data to the aerobot; insect rover/hopper downlinks to the Nanorover or microrover or Lander in turn; and the Burrower communicates to the Penetrator. Such a heirarchical organization allows a more composite, widespread and affordable avenue for exploration.

2. OBJECTIVE: The overall objective of this task is to conceptualize and develop insect explorers for future missions. The specific objective of this task is to conceptualize, design, and develop the insect rover/hopper variety of insect explorers for future missions. These will serve to complement/supplement the science functions performed by traditional rovers and perform certain dedicated sensing functions in hazardous /new territory that is normally inaccessible to conventional means of exploration owing to their size and cost. Their significant function will be IN-SITU SENSING and ATMOSPHERIC INFO gathering combined with localized surface exploration at the landing locale of the rover/hopper.

3. JUSTIFICATION: There is a need to develop a NEW BREED of Nanorobotic Exploring Vehicle - the Insect Explorers that have MEMS based Advanced Mobility combined with dedicated on chip Sensing. Such explorers will serve to complement/supplement the science functions achievable by traditional rovers. The Insect Explorers will be low mass, LOW COST - can be easily accommodated in the mass reserves of the mission, will allow exploration of hard to reach, normally inaccessible or hazardous locations. For such high risk mission goals, expendability - ultra low production cost is the key -which is sought for by MEMS based production of such explorers. This need for low cost insect explorers for planetory exploration becomes specifically crucial in light of the challenge we have for human and robotic missions for exploration of the solar system by devicing AFFORDABLE, NEW, RELIABLE exploration systems and techniques.

4A. PAY-OFF:

The pay-off includes:

* Extremely small size - allows reach to places never reached before for in-situ sensing
* Expendable due to low cost - will be used to explore high risk zones
* Science return /$ would be tremendous, unprecedented.

4B. SIGNIFICANT FUNCTION OF INSECT **EXPLORERS:** Scouting Missions to hard to reach new locations and hazardous locations. These expendable insect - explorers complement & supplement the function of the fully geared traditional rovers by EXPLORING OTHERWISE UNAPPROACHABLE OR HIGH RISK TERRITORY AT A LOW COST RISK. The significant functions will include exploratory imaging combined with in-situ sensing such as for water or carbonates for fossil/life sensing.

4C. KEY FEATURES - INSECT **EXPLORER:**

1. A BREAKTHROUGH IN SIZE REDUCTION - upto two orders of magnitude reduction in the size of motors/ leg actuators will be achieved.

the piezoceramic technology has been selected to achieve this goal. Innovations offered by this technology of the PLZT family of piezoceramics, specifically those of a thin film MEMS **PIEZOMOTOR** and **PHOTOACTUATING** CANTILEVER LEG will be demonstrated. Such microactuators will be utilised for surface/sub-surface micromobility as well as light weight aerial sampling needs.

2. LONG DISTANCE TRAVERSE

localised exploration on surface/subsurface utilising mobility on ground by piezoceramic actuation mechanisms in one species will be combined with flight/hopping mechanisms for long distance traverse in another species within the swarm of insect explorers.

3. SCIENCE VALUE - BOTH SURFACE/SUBSURFACE EXPLORATION & ATMOSPHERIC INFO GATHERING.

is attainable by the entire swarm of explorers consisting of Surface Rovers, Hoppers, Burrowers, Flyers, all species put together. Furthermore, the small size allows it to approach the subsurface through wide cracks/crevices and thereby gather **non-invasively** pristine samples hidden underneath.

4. LOW COST - EXPENDABLE

silicon batch processed - lower cost manufacturing techniques

5. ENVIRONMENTALLY RELIABLE - WIDE TEMPERATURE RANGE OF OPERATION

- the use of robust actuators (such as piezoceramic) and sensor chips will offer good cyclability and wide temperature range of operation.

6. OPTION Of TETHERLESS PHOTONIC/ DIRECT SOLAR DRIVE

- Photoactuation in PLZT offers potential of tetherless operation by means of a remote controlled tetherless photonic drive or even the possibility of direct solar drive.

5A. APPROACH:

Mimicking biology to produce these artificial insects for dedicated sensing functions is attainable by combining the following:

1. **Advanced Mobility:** Breakthrough in size reduction of actuators offered by thin film piezoceramics will be utilized for advanced micromobility and the light weight sampling needs. Innovations in

burst optical/electrical surge techniques will be utilised to obtain the boost for hopping/flight projectile motion.

2 Utilizing the cutting edge technology in On-chip **Sensing/Imaging**.

3. Utilizing innovations in **Communications** for Extracting the sensed data.

5B. ADVANCED MOBILITY:

I. TECHNICAL CHALLENGES:

1. small, simple, reliable, low power budget micro-mobility
2. mars environment, low temperature operation
3. low cost, expendable micro-mobiliy for nanochippers, nanoscrapers (LIGHT WEIGHT SAMPLING TOOLS & MANIPULATORS)

II. APPROACH

The approach items correspond to each of the above challenges:

1. With size reduction, the energy absorbed by piezoceramics can be upto over two orders of magnitude higher compared to electrostatic & magnetic actuators (Figure 2). TABLE 1 compares the different actuation technologies and clearly illustrates why piezoceramics are the leading candidate for actuation, specially so - as we scale down and approach the thin film domain where properties are tailorable to optimum by fine composition control. Piezoceramics stand out for the high torque, wide temperature operability, cyclability and good potential for miniaturization. Furthermore, piezoceramics offer the potential of solar driven, tetherless mechanisms since they can be actuated directly by optical illumination (350nm to 450 nm) as illustrated in Fig 3.
2. piezoceramic actuation potentially robust, amenable to low temp operation. high radiation etc.
3. batch production by Si compatible manufacturing techniques offers redundancy -expendability

THE APPROACH OF THIS TASK IS THEREFORE TO DEMONSTRATE THESE BREAKTHROUGHS OF PIEZOCERAMIC TECHNOLOGY FOR SIZE REDUCTION OF MOBILITY APPLICATIONS. Figure 4 illustrates the two pronged approach that is proposed. The far term, high payoff new phenomena approach of the directly solar driven high efficiency bimorph will be leveraged along side with the alternate well established, near term approach of travelling wave piezoceramic motors (solar driven in combination with solar cells). The challenge in the first approach is that of designing a SELF SUSTAINED MOBILE DIRECT PHOTODRIVEN LEG/ACTUATOR as shown in figure 5 based on the high efficiency bimorph (figure 6). The challenge in the second approach is to design and microfabricate the THIN FILM PIEZOCERAMIC MOTOR (figure 7 &8)- and further design a gearless, transmission less micro-mobility component -the piezo-wheel (figure 9&10). Figure 9 illustrates a flip-chip conjuration of a dual stator thin film piezo-motor configured as a piezo wheel.

6. TASKS & DELIVERABLES:

FY'97:

a. Develop full Conceptual Design of the Insect Explorer including the key component subsystems:

1. Mobility Mechanisms (a Prime Subsystem)
   - Surface/Subsurface Mobility mechanisms

   Survey Aerial Mobility Mechanisms such as Hopping, Flying etc. Select mechanism and develop the design to obtain a insect-hopper/flyer utilizing innovations in burst optical/electrical surge to obtain the boost for hopping/flight projectile motion.
2. Sensing (application & mission specific, mobility and sensing combinations are interdependent based on mission needs)

3. RF/Optical Communications for sensor data downlink / no tele-communications (hopper/flyer comes back to lander for stored sensor data readout at lander). Trade study to ascertain the most suitable way to downlink sensor data.
4. Computing & Processing (minimal), Controls & Navigation (preprogrammed)
5. Power (High Efficiency Solar cells/ compact Batteries~ 3 V or direct optical/solar operation - based on application choice)

b. Key experiments will be performed to validate the feasibility of the conceptual designs. The mobility approach for demonstration will be selected based on this initial concept assessment.

FY'98: Insect Explorer: Rover/Hopper Design Optimization and proof of concept demo of final design.
FY'99: Demonstrate Insect Explorer Mobility Prototype
FY' 2000: Integration of Sensing payload on Insect Explorer
- Prototype Demonstration

FY' 2001: Demonstrate Insect Explorer

DUAL USE POTENTIAL:

Such microminiaturized explorers are required for security and intelligence purposes. Commercial vendors will seek this technology for a variety of nanorobotic applications. DOD (ARPA) has synnergistic interest in this kind of rovers. The nanoactuation technology so developed WILL synnergistically be applicable to micropositioning applications in the imaging and adaptive optics domain.

COST: FY'	97	98	99	2000	01
	280K	550K	650K	750K	800K

OTHER SYNNERGISTIC SPIN-OFF BENEFITS:

1. Advaced Nanoactuation for future NASA Missions.
   - the Gossamer Spacecraft.

2. commercial and DOD applications such as burrowers for sensing life in earthquake rubble or other such disaster zones. Security and intelligence surveillence (under the door roving imagers). Scouting for poisonous gases in mines.

3. Bio-medical Applications such as non-invasive/minimally invasive surgery.

4. ARPA holds interest in a rover similar to the Insect-Rover/ Flyer

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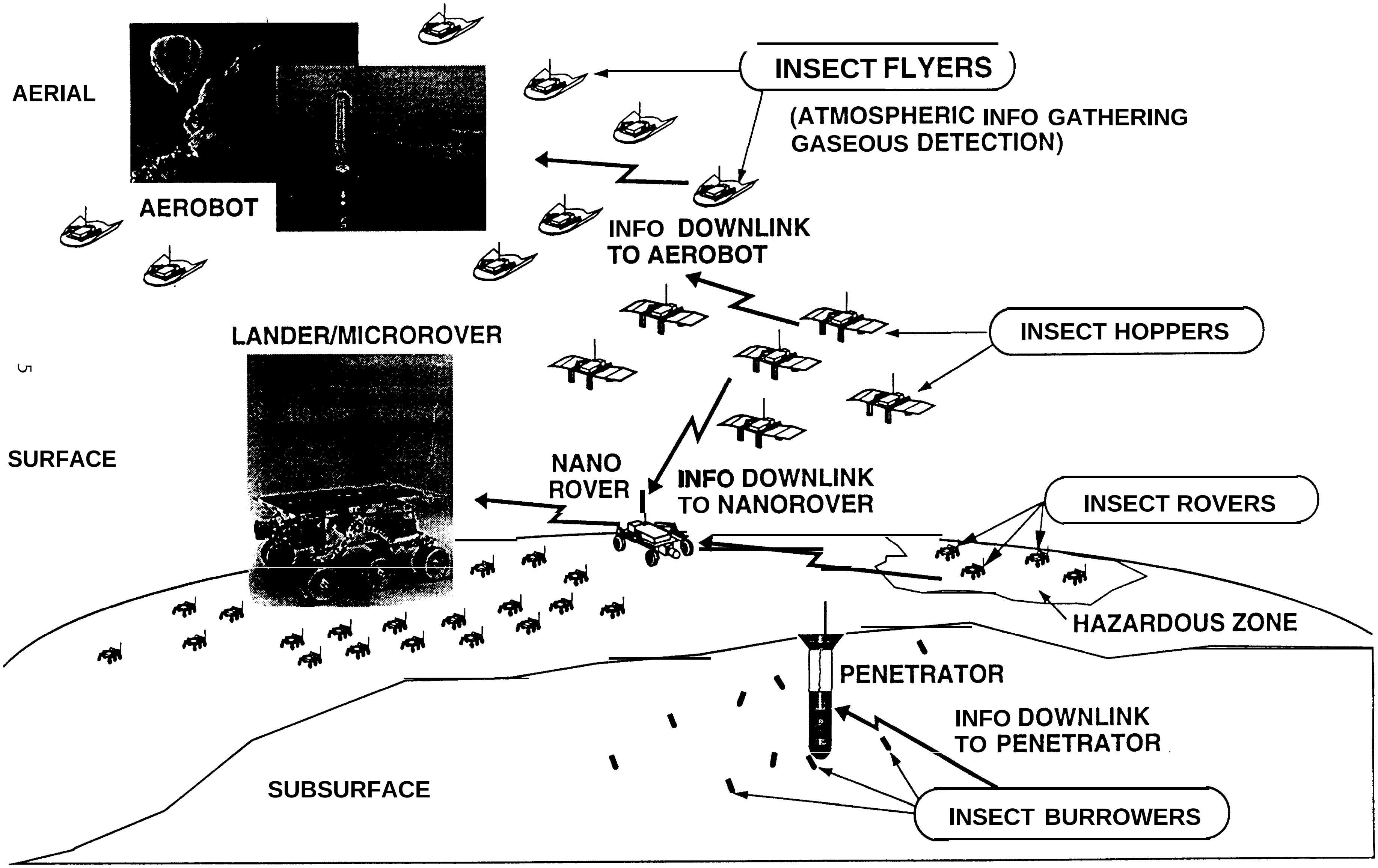
INSECT EXPLORERS

HEIRARCHICAL ORGANIZATION: ALLOWS COMPOSITE, AFFORDABLE EXPLORATION OF THE SOLAR SYSTEM



SARITA THAKOOR
VISION XX

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WHY PIEZOELECTRIC ACTUATION?

(AS WE SCALE DOWN TO THIN FILM PIEZOCERAMICS)

			POLYMERIC	MATERIALS	
	PIEZOELECTRIC	SHAPE MEMORY ALLOY	PVDF	POLYMIDES PMMA	MAGNETO-STRICTIVE
MECHANISM	PIEZOELECTRIC & ELECTROSTRICTIVE	THERMAL: MARTENSITIC → AUSTENITIC PHASE CHANGE	PIEZOELECTRIC	ELECTRO-STRICTIVE	MAGNETIC FIELD INDUCED BY COIL
STRAIN	10^{-4} TO 10^{-2}	10^{-5} TO 10^{-3}	10^{-6} TO 10^{-5}	10^{-9} TO 10^{-3}	10^{-5} TO 10^{-2}
TORQUE	HIGH ~100 kgm FORCE	LOW-MEDIUM ~1kgm FORCE	SMALL	SMALL	HIGH
HYSTERESIS	TAILORABLE BY COMPOSITION	SMALL	LARGE	SMALL TO MEDIUM	LARGE
AGING	COMPOSITION DEPENDENT	VERY SMALL	LARGE	LARGE	SMALL
TEMPERATURE RANGE OF OPERATION	–196°C → 300°C WIDE	–196°C → 100°C WIDE	–10°C → 60°C LIMITED	–10°C → 80°C LIMITED	-273°C → 100°C WIDE
RESPONSE SPEED	µsec-msec	seconds	msec	msec	µsec-msec
ACTIVATION MODE	BOTH OPTICAL AND ELECTRICAL	THERMAL AND ELECTRICAL	ELECTRICAL	ELECTRICAL	MAGNETIC
POWER REQUIREMENT	Low	LOW	MEDIUM	LOW TO MEDIUM	HIGH
RADIATION HARDNESS	YES	TBD	TBD	TBD	YES
CYCLABILITY	EXCELLENT	GOOD	FAIR	FAIR-POOR	GOOD
PROSPECT OF MINIATURIZATION	GOOD	GOOD	GOOD	GOOD	FAIR

PIEZOELECTRICS REPRESENT A LEADING CANDIDATE FOR ADVANCED NANOACTUATION

COMPARISON ACTUATION TECHNOLOGIES

ENERGY DENSITY AS FUNCTION OF THICKNESS

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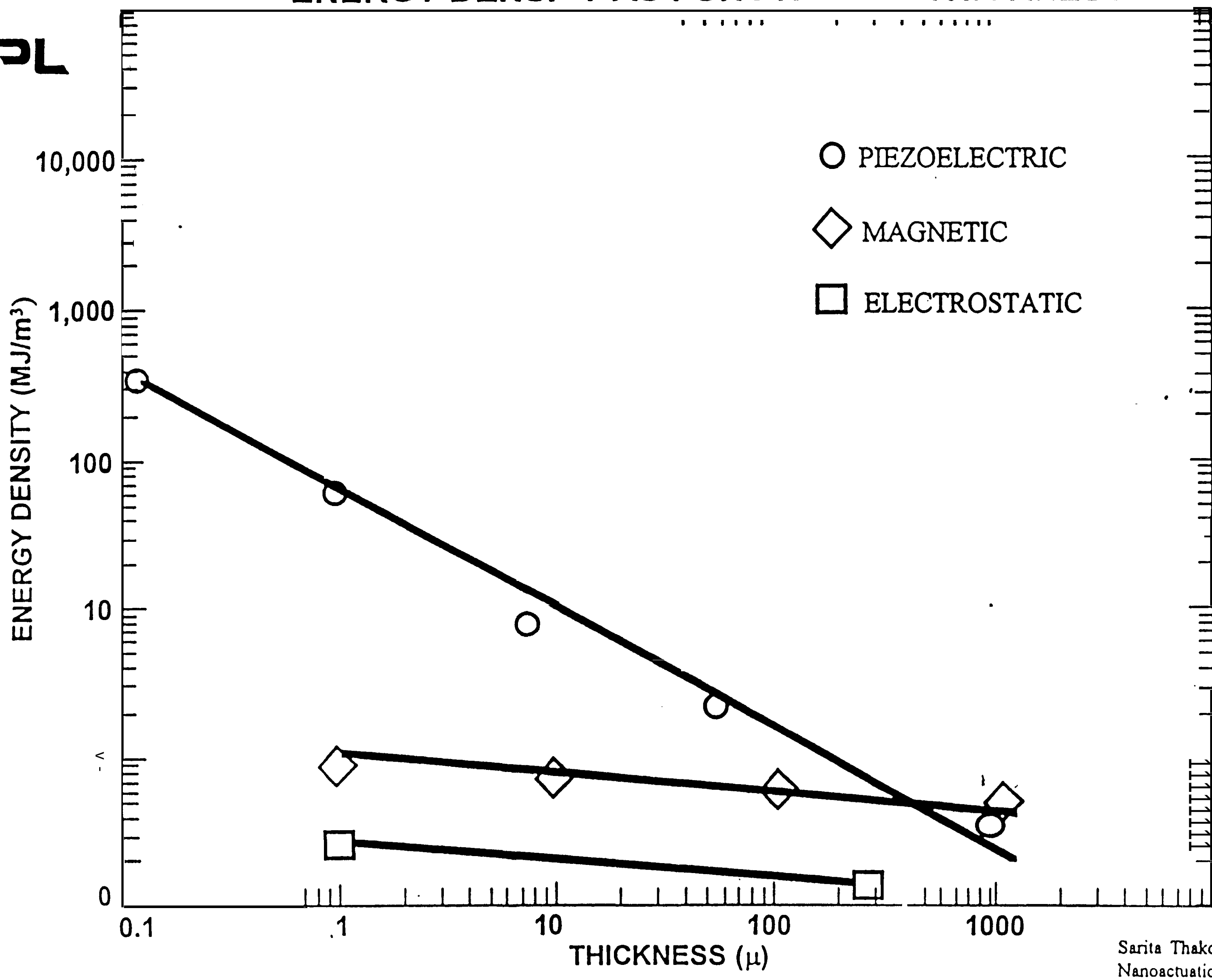

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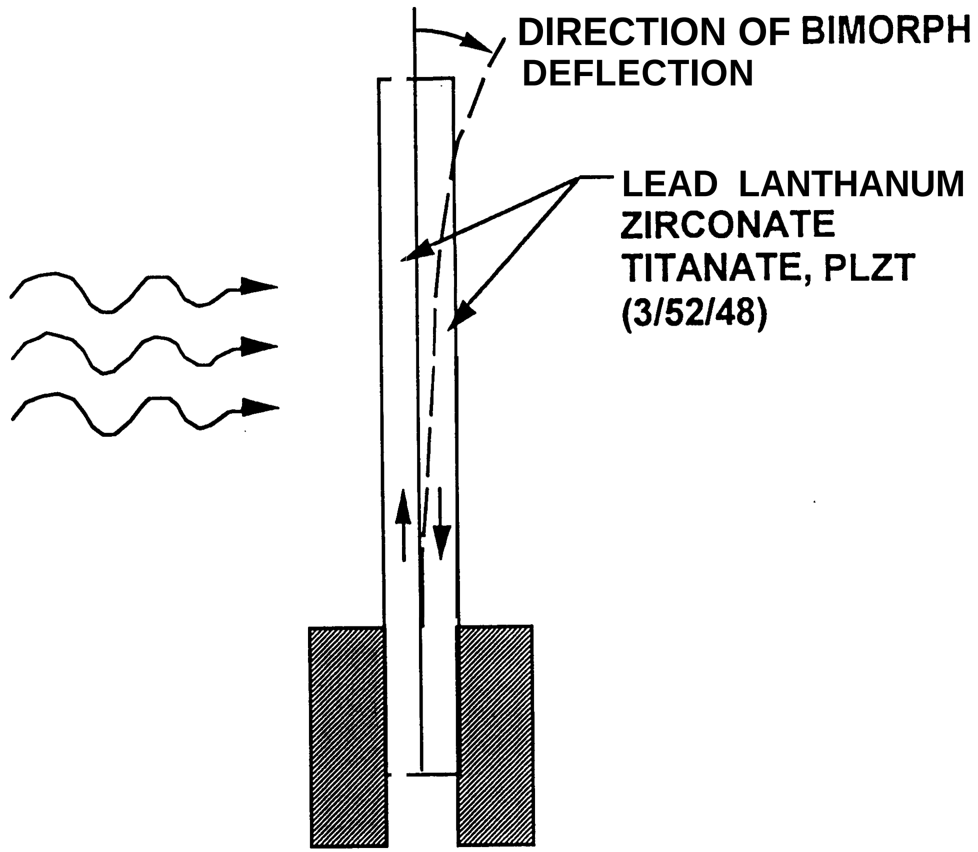
Nanoactuation

JPL PHOTODEFLECTION OF PLZT BIMORPH



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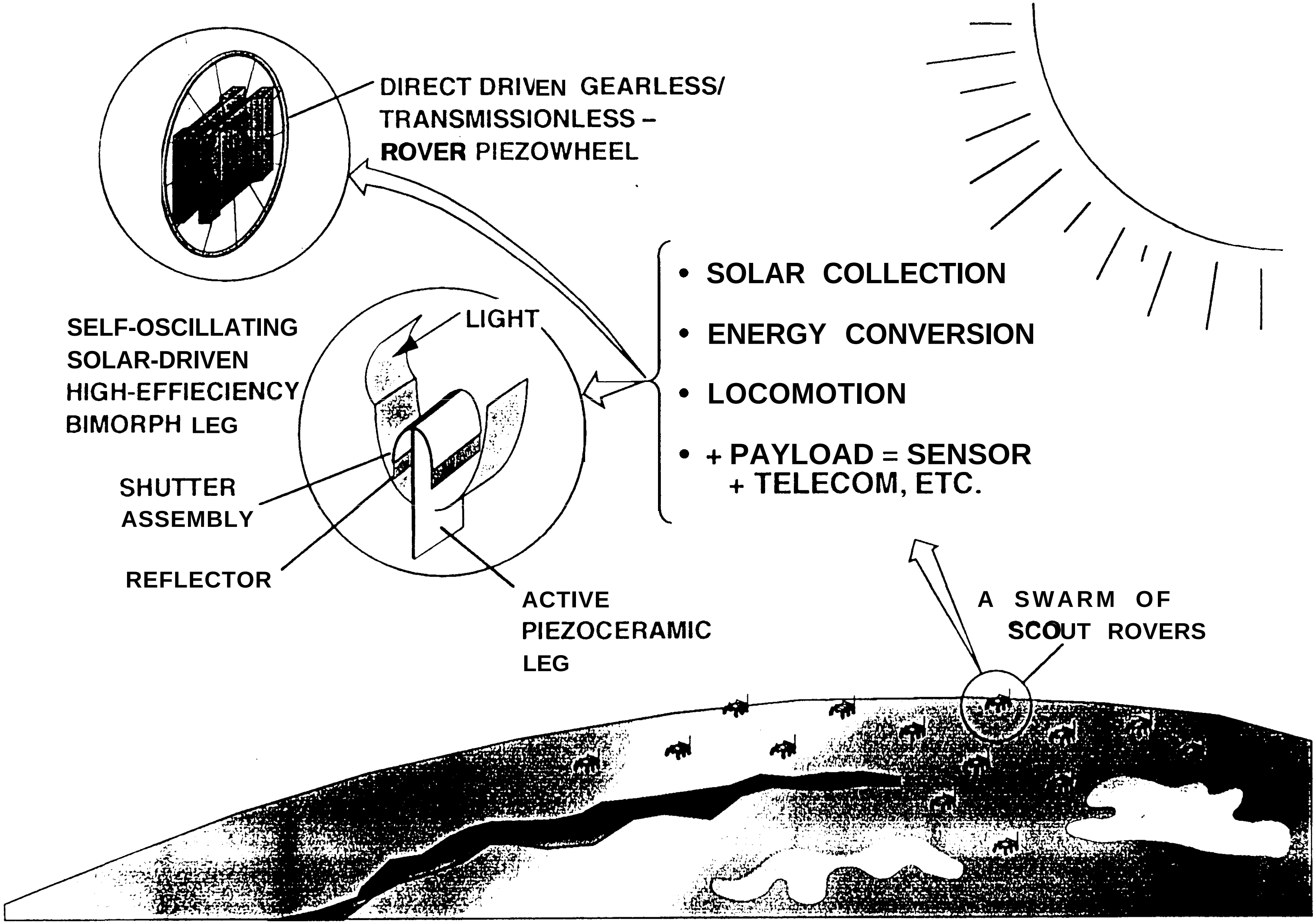
JPL SOLAR DRIVEN TETHERLESS SCOUTROVER



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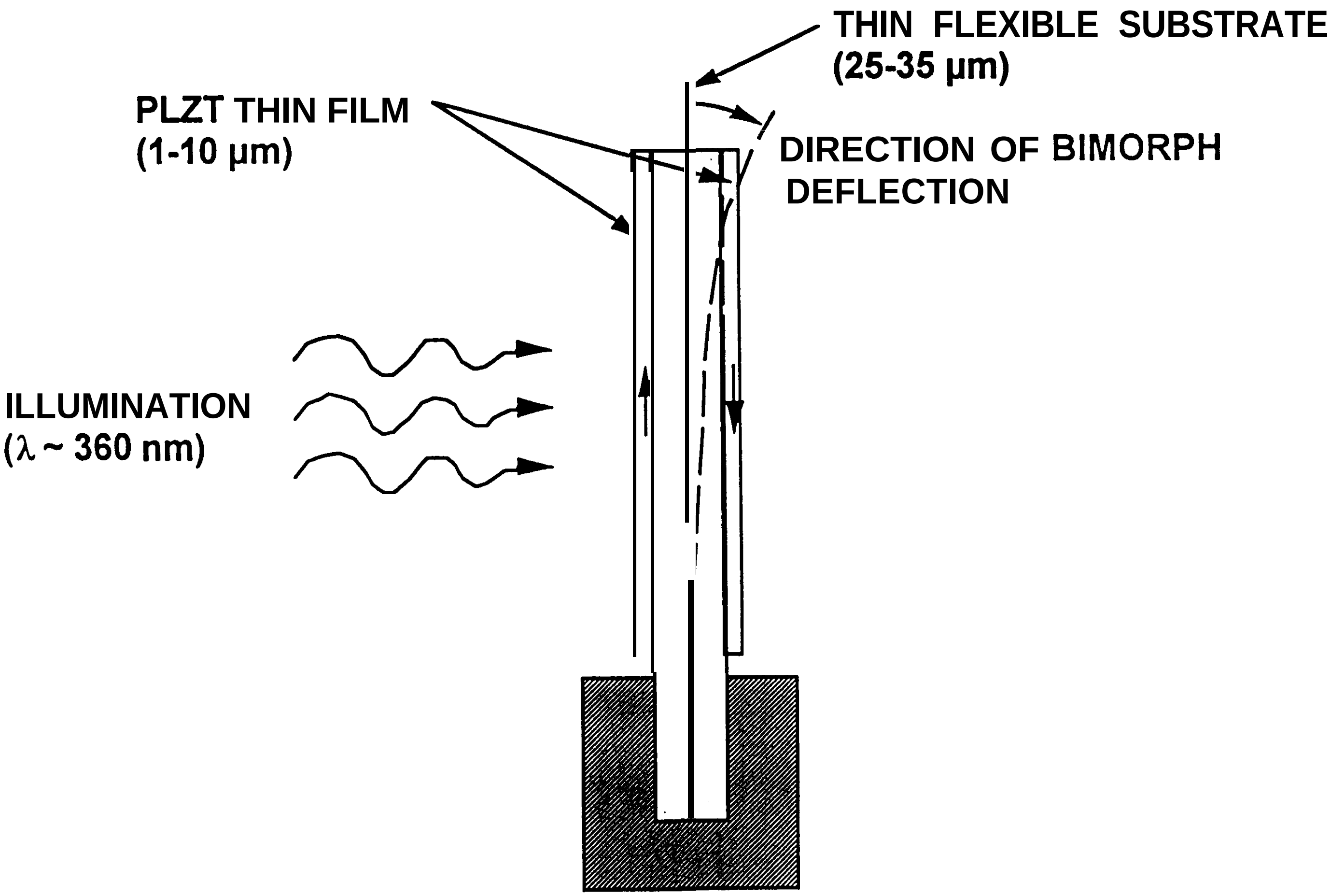
PEER REVIEW 8

HIGH EFFICIENCY THIN FILM MICRO-MECHANICAL PLZT B! MORPH



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PHOTODEFLECTING BIMORPH DEVICE

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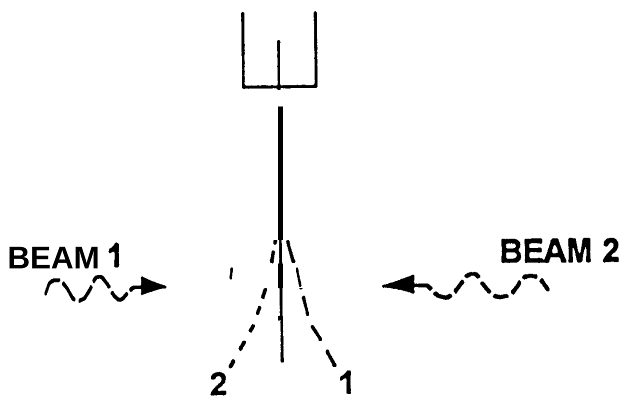
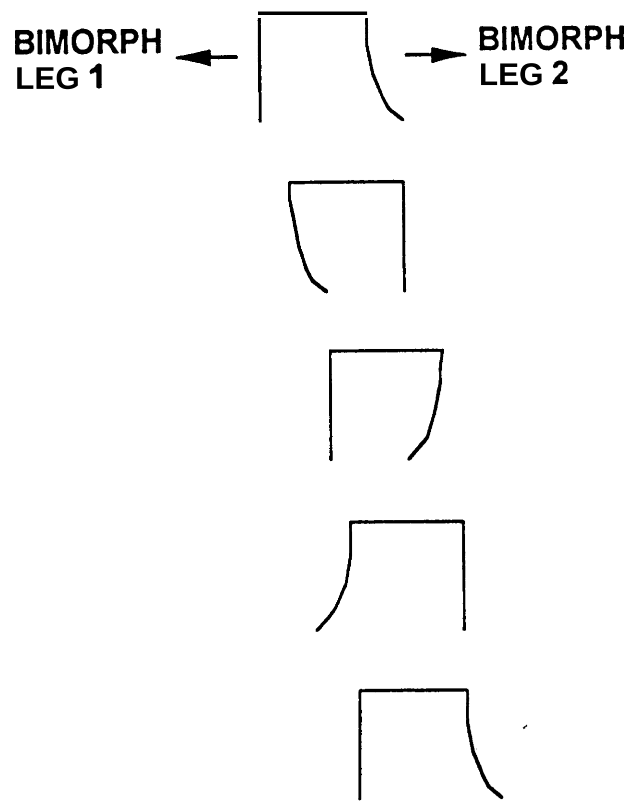
BASIC PRINCIPLE ALTERNATING DEFLECTION OF INDIVIDUAL BIMORPH DEVICE



ALTERNATING PHOTODEFLECTION OF THE BIMORPH WHEN ILLUMINATED WITH ALTERNATING LIGHT PULSES FROM THE TWO SIDES

INCH WORM TYPE TRANSLATIONAL MOTION OF TWO LEGGED BIMORPH DEVICE



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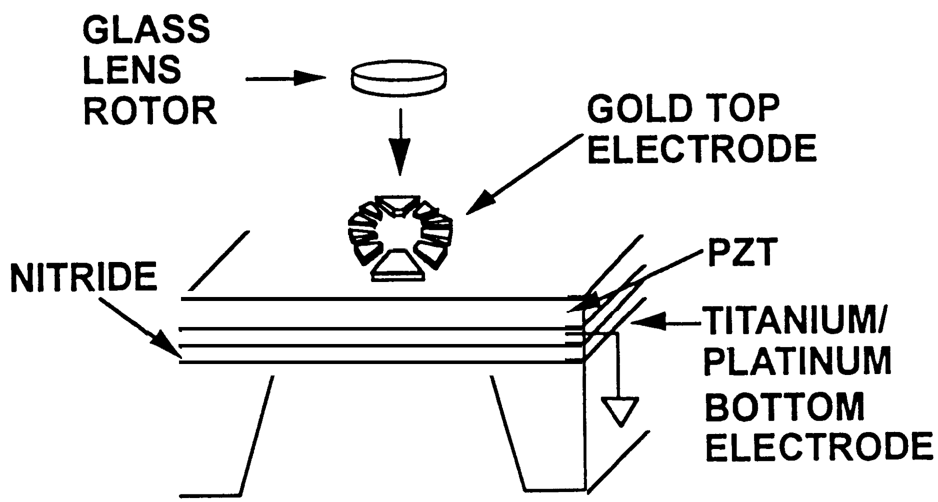
JPL THIN FILM PIEZOELECTRIC MOTOR



STATOR STRUCTURE

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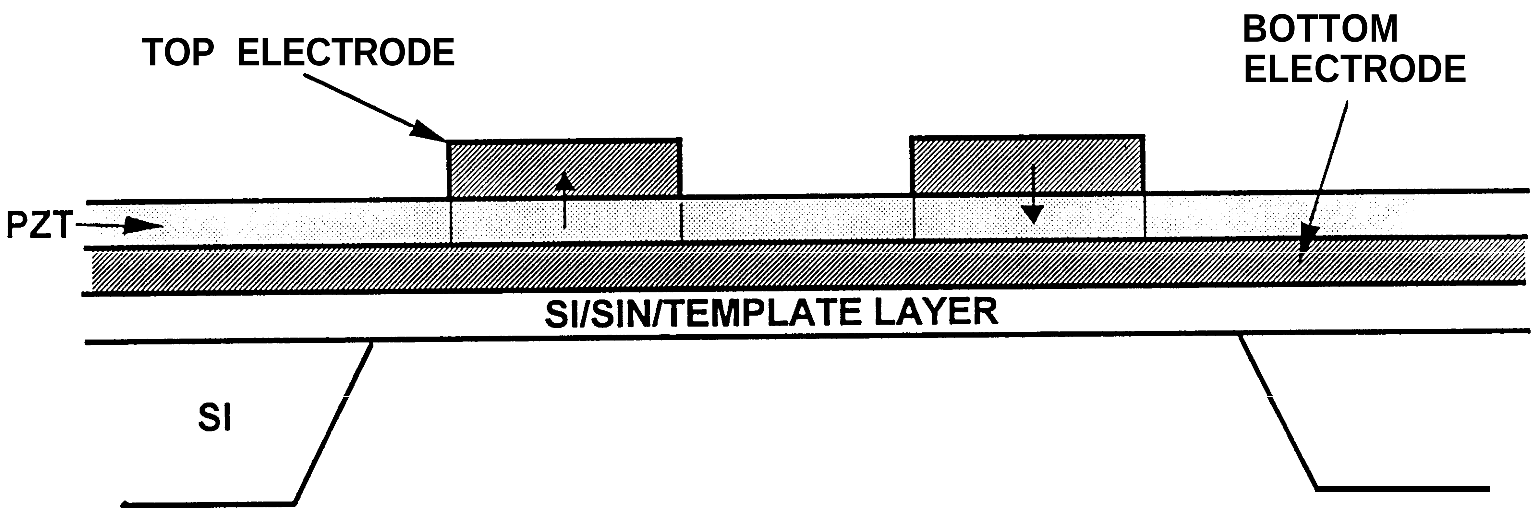
THIN FILM PIEZOCERAMIC MOTOR



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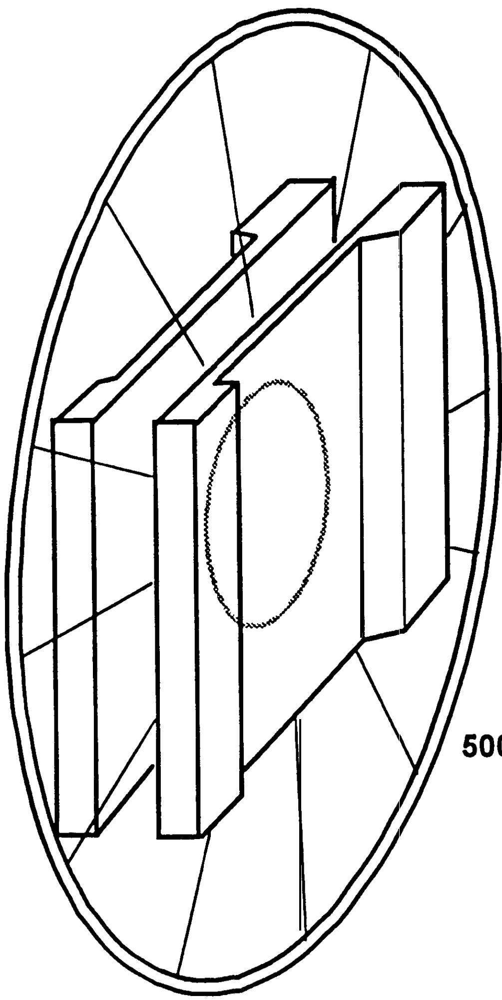
THIN FILM PIEZOCERAMIC MOBILITY SY



- DIRECT DRIVEN
- GEARLESS/TRANSMISSION L
- THIN FILM PIEZOCERAMIC WI

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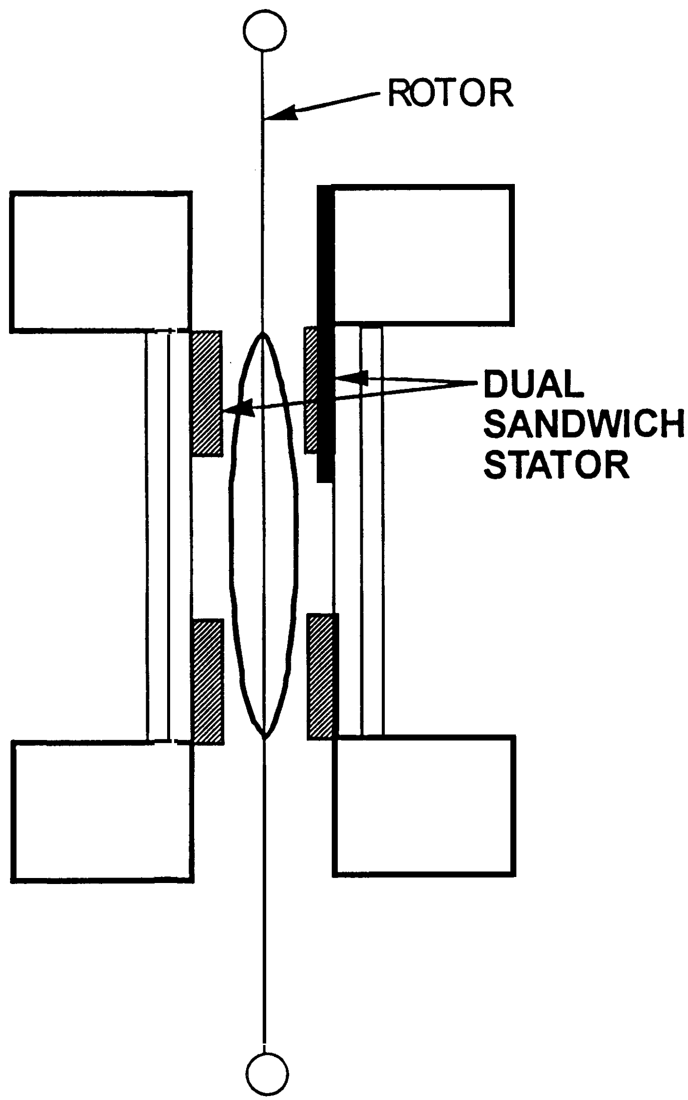
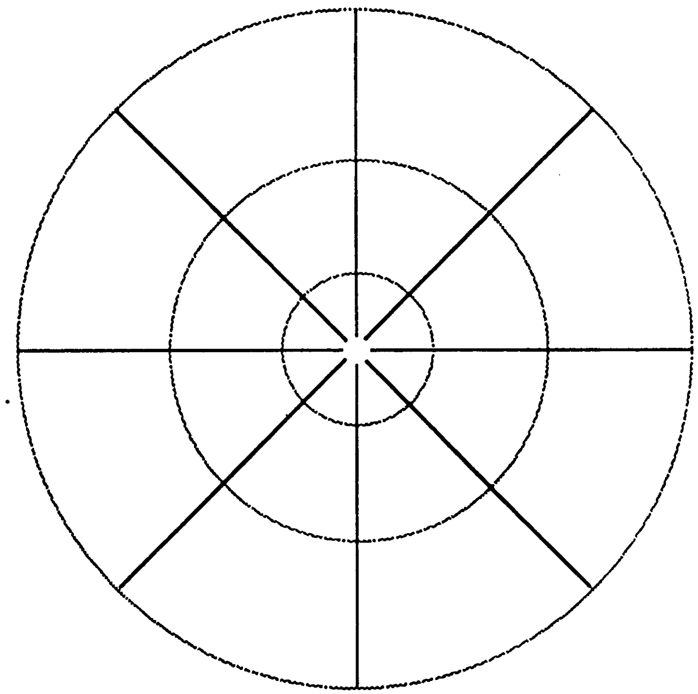
THIN FILM PIEZOCERAMIC MOTOR





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