Bioinspired Engineering of Exploration Systems
From 'bees' to "BEES for MARS"

Biomorphic Flyers for Mars Exploration

March ~~Feb 3~~, 2003

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~~Update provided to Sec 311/Div 31 line management~~

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Robotic Planetary Exploration Requirements

- Mobility in very rugged terrain
  - The most interesting science sites are often the most inaccessible
- Sensing
  - Multispectral Science Imagers
  - Stereo and Ranging
  - Navigation
- Manipulation
  - Sample/Measurement Preparation
  - Sample Acquisition
  - Digging/Drilling
- Communications
  - Low-bandwidth
  - Time-delayed
- Decision-making
  - Path-planning
  - Resource Utilization
  - Health and Safety

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Mission Design Trades

Designs involve a trade-off between:

- Capability of the System
  - Science Return
  - Complexity
  - Reliability
- Mission Resources
  - Mass
  - Power
  - Consumables

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Earlier Design Philosophy

In earlier decades of space exploration, these trades often resulted in very large and complex spacecraft with very capable (and expensive) instrumentation. These systems were so expensive to design and build that they were operated in a very risk-adverse manner. It was not acceptable for these missions to fail.

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Recent Design Philosophy

In more recent years we have experienced a shift towards smaller and less expensive spacecraft (with less capability). Because these systems were less expensive and flew more often, a certain amount of increased mission risk was deemed acceptable as a result of more aggressive use of new technology.

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Current Design Philosophy

Having experienced the extreme ends of this cost/capability spectrum, we are currently seeing a shift back towards the middle ground with larger and more capable systems with increased use of new technology. We are still oriented towards risk-adverse operations, however, it limits the amount and quality of science return from currently planned exploration missions.

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Promise of Biologically-Inspired Systems

Biological organisms overcome many of the limitations of current state-of-the-art robotic exploration systems in several areas:

- Increased Mobility: Access and Safety
- Efficient Sensor Processing and Interpretation
- Compliant and Dexterous Manipulation
- Efficient Communication/Coordination Strategies
- Computationally-Efficient Decision-Making

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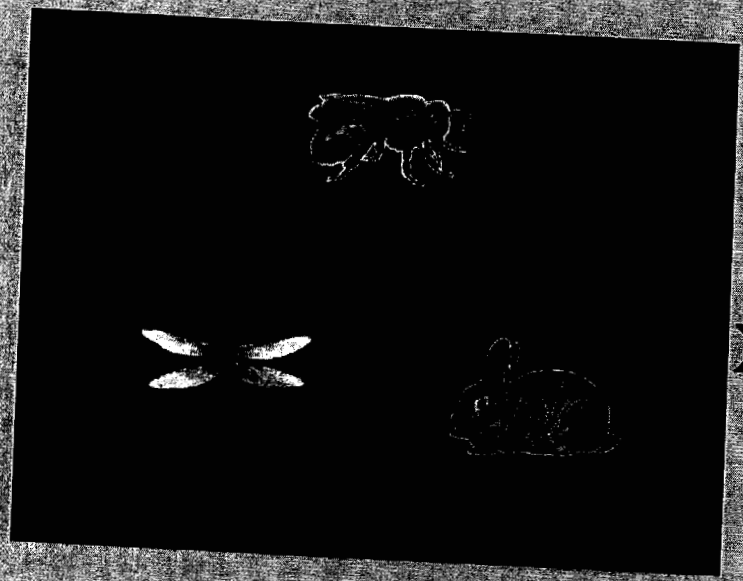
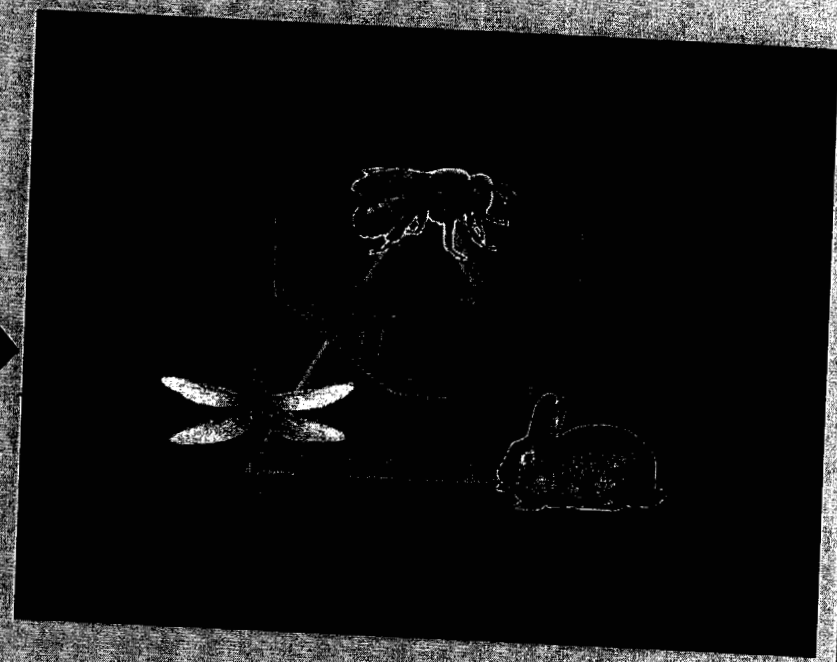
Combine "best-of-class" capabilities…





…to produce an extremely capable hybrid.

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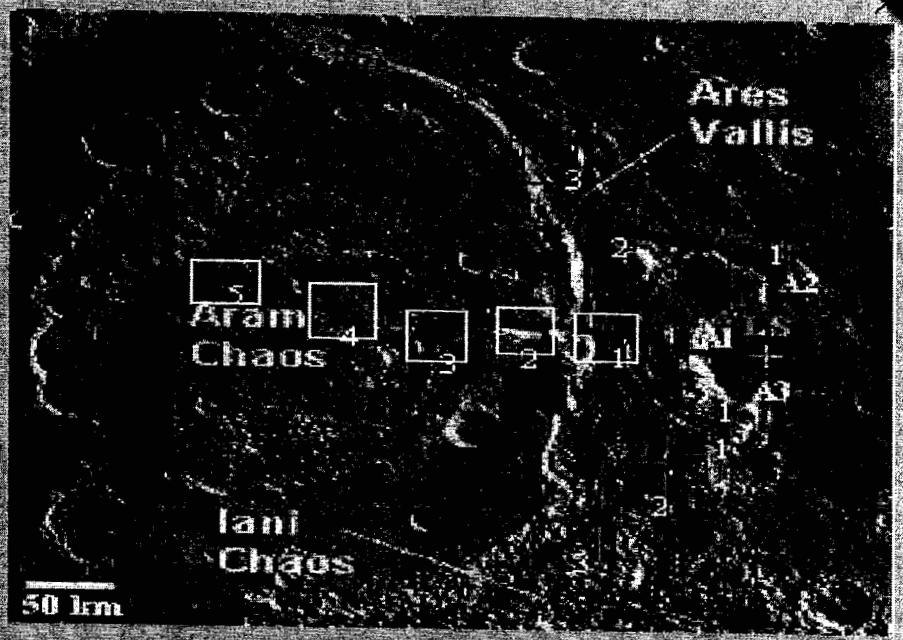
BIOINSPIRED ENGINEERING OF EXPLORATION SYSTEMS

Aram Chaos Site



FUTURE MARS EXPLORATION: KEY REQUIREMENTS:

- Large exploration range ~10 -1000 Km
- Send many explorers: Big impact for Small size payload
- Ability to provide high resolution (5cm - down to tens of microns)
  - Stable low altitude aerial imaging
  - Altitude hold while imaging to obtain desired detail
  - Precision approach to desired site (precision navigation)
  - Distributed measurements at site of interest
  - Explore Canyons, Craters, Gullies that are Unreachable heretofore.

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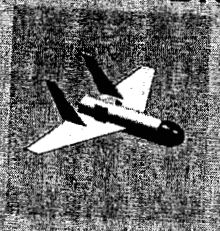
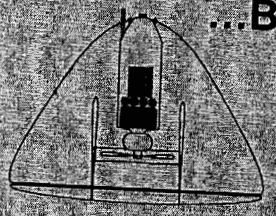
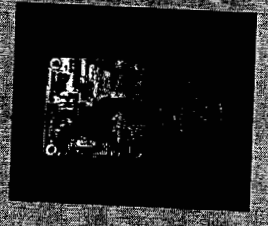
Biomorphic Microflyers

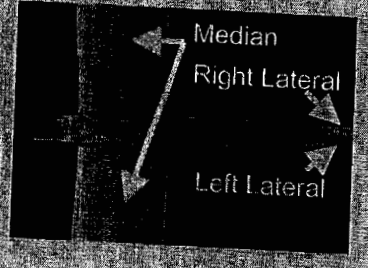
- WHY MICROFLYERS? HUGE RANGE, AERIAL COVERAGE FOR LOW MASS(~ 1 Kg each flyer explorer)
- BIOINSPIRED: FORM (SMALL SIZE –WINGSPAN 15 cm to ~ 1m), FUNCTION, BEHAVIOR



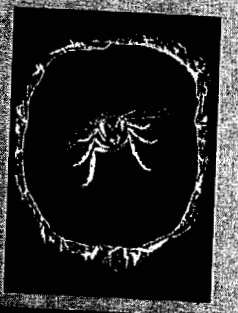




BIOMORPHIC OCELLUS IMPLEMENTATION



...BIOINSPIRED FLYERS



INNATE ABILITIES:
- NAVIGATION
- ALTITUDE HOLD
- TERRAIN FOLLOWING
- COOPERATIVE STRATEGIES

COGNITIVE ABILITIES
- PATTERN RECOGNITION
- ADAPTIVE CONTROL, RECONFIGURABILITY
- RETINAL TECHNIQUES – IMAGE ENHANCEMENT

SCIENCE GOAL FOR MARS:
"FOLLOW THE WATER" →
LOCATE WATER FLOW FEATURES, NAVIGATE TO THEM , IMAGE THEM CLOSE-UP AND DEPLOY INSTRUMENTS AT SUCH SELECTED SITES FOR DETAILED IN-SITU, DISTRIBUTED MEASUREMENTS

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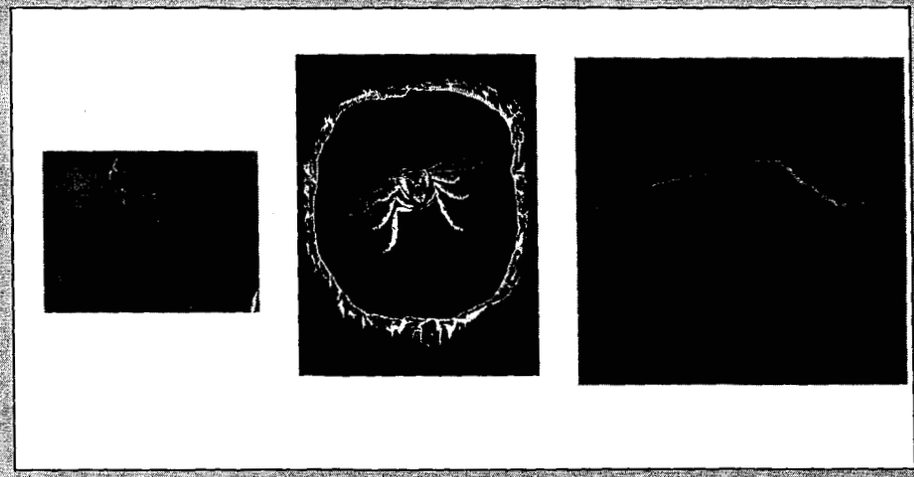
Biomorphic Navigation

Insects (for example honey bees) cope remarkably well with their world, despite possessing a brain that carries fewer than 0.01% as many neurons as ours does. Although most insects have immobile eyes, fixed focus optics(no range info) and lack stereo vision, they use a number of ingenious strategies for perceiving their world in three dimensions and navigating successfully in it. We are distilling some of these 'bee' inspired strategies to obtain unique solutions to navigation, altitude hold, stable flight, terrain following and smooth landing. Our focus is on exploring the feasibility of incorporating these success strategies in our biomorphic flyers for future missions

- BIOMORPHIC OCELLUS BASED ON DRAGONFLY OPTICAL STABILIZATION ORGAN
- HONEY BEE INSPIRED OPTIC FLOW SENSOR
- NAVIGATION USING SUN AND POLARIZATION COMPASS
- BIOMORPHIC PANORAMIC IMAGER
- HAZARD AVOIDANCE AND TERRAIN FOLLOWING
- LANDING AND INSTRUMENT DEPLOYMENT STRATEGIES



Karl von Frisch, 1965
Wehner and Rossel, 1985
Srinivasan et al, 2000, 1997
Chahl et al, 2000

Honeybee Inspired altitude hold, stabilised flight, terrain following, gorge following, obstacle avoidance and precision point-to-point navigation

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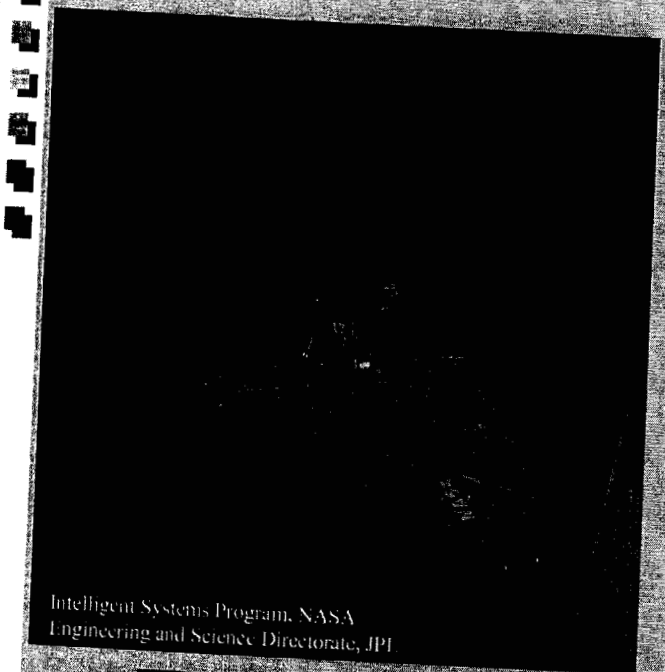
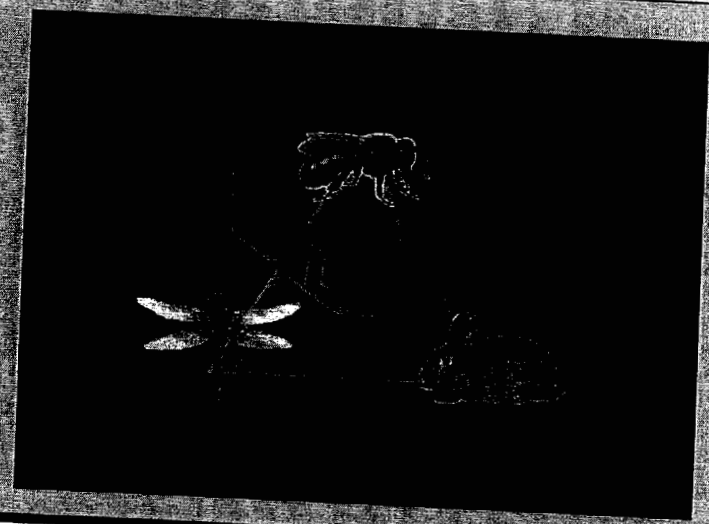
BIOINSPIRED ENGINEERING OF EXPLORATION SYSTEMS



• 2001 SIGNIFICANT ACCOMPLISHMENTS

* Demonstrated World's first "biomorphic ocellus"- insect-inspired, light weight (~ 6 g is X40 lighter than existing inertial navigation units) flight stabilization system
* Demonstrated World's first "biomorphic flyer" platform Its highlight's include:
* Delta Wing design : robust to ~ 40G capability
* Ease of stowing and packaging
* Can fly at high angles of attack ~ 30°
* Deep chord of the wing allows scaling to small size and low Reynold's number performance
* Will use biomorphic sensors for navigation and pattern recognition

Significance: These developments pave the foundation to enabling MARS capable biomorphic flyers



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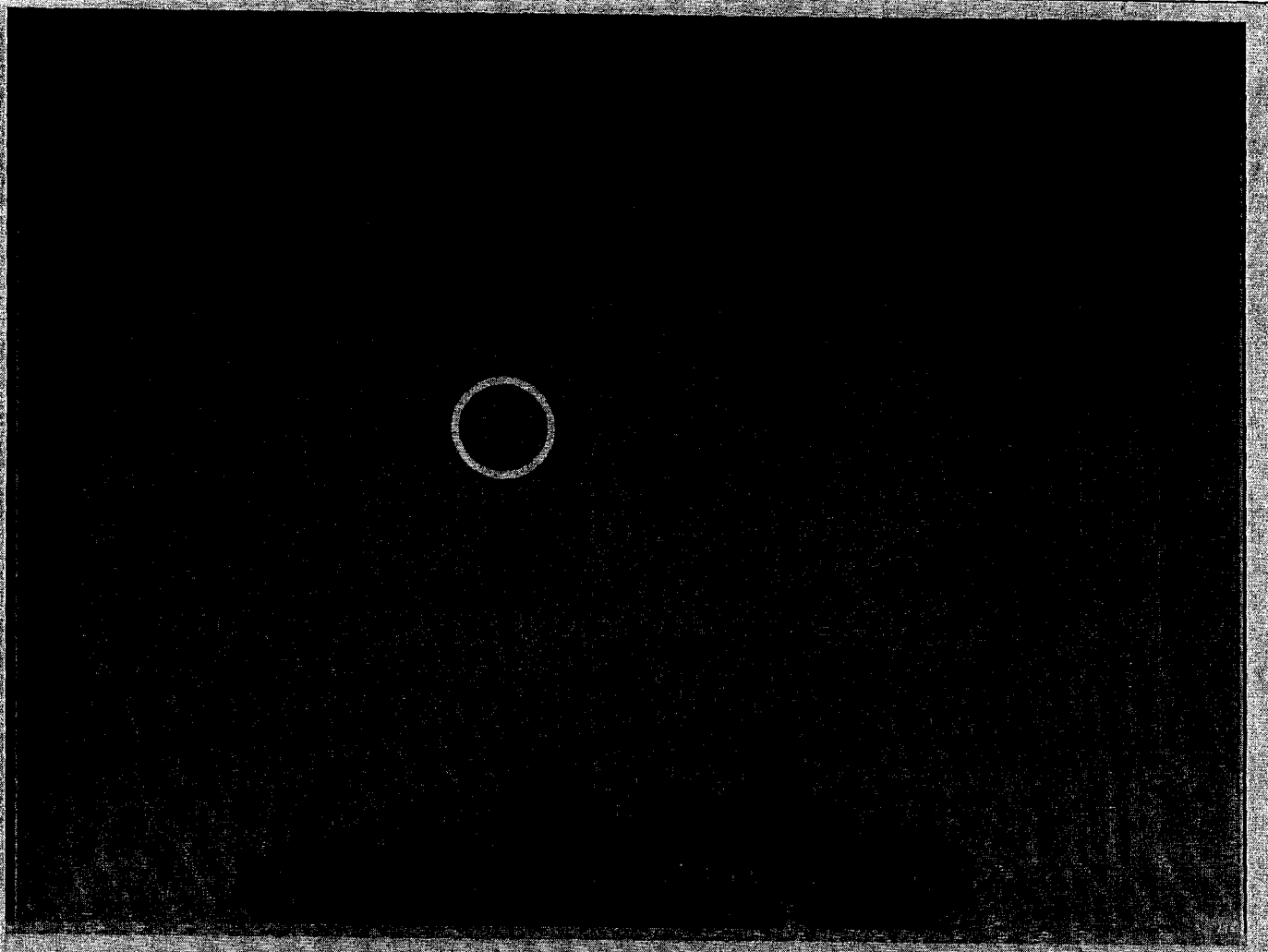
BIOMORPHIC FLYER (1.5Kg) PROTOTYPE



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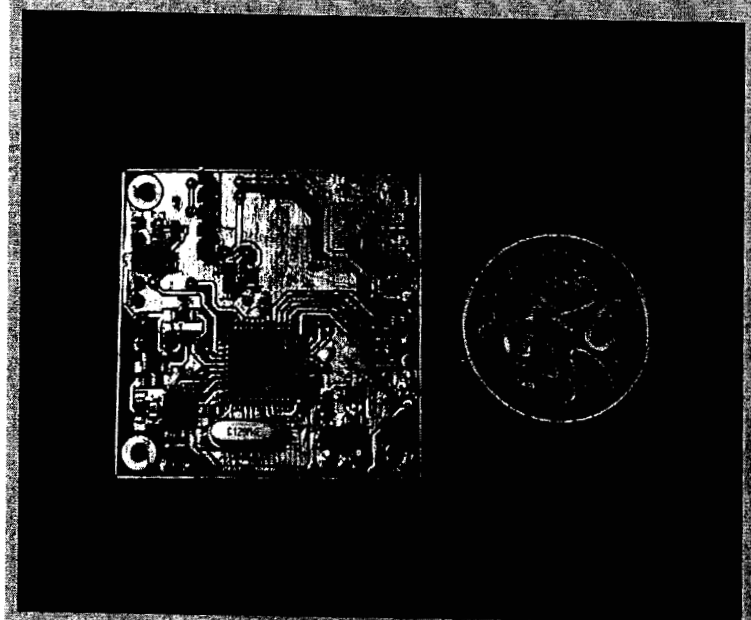
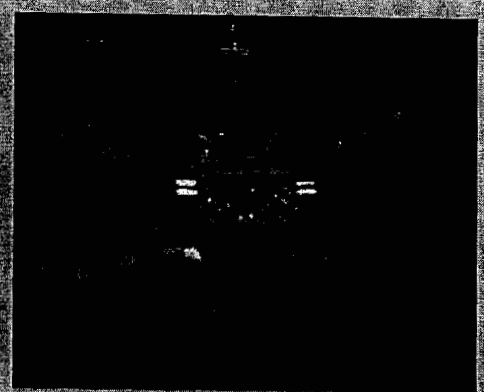
Bioinspired Engineering of Exploration Systems

- World's first embedded biomorphic ocellus (horizon sensor) built and successfully flight tested. Mass: 6 gm, Power ~ 40 mW, 3.5cmx2.5cm



Horizon stabilization sensor modeled directly from the ocelli of dragonflies.

Mass 6g, Power 40mW



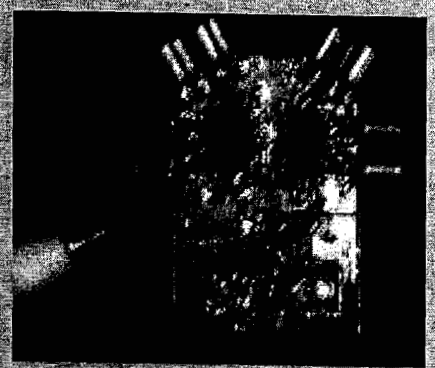


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Table 1: Evolution of the Ocellus

Feature	COTS inertial vertical reference (surface mount)[1]	Custom inertial vertical reference (Die level)[2]	COTS ocellus (Hybrid digital/analog)[3]
Mass	100 g	25 g	6 g
Voltage	5V	3.3V	2.9V
Current	100mA	40mA	15mA
90 degree phase shift frequency	90Hz	-	2kHz
Min light level	Immune	Immune	0.01 lux
Autopilot requirement	DSP	DSP	µcontroller
Thermal stability	Poor	Poor	Excellent
Thermal range	-20 to +70	-	-50 to +90
Rotation/Acceleration/Cross Axis coupling	Some	Some	None

1. Note, the size of the COTS inertial unit, and the performance parameters are based on a system built to the minimum possible size using surface mount technology by our group in mid 2001.
2. Note the size of the custom inertial unit is based on the die level products from companies such as Analog Devices.
3. The COTS ocellus is based on the performance parameters of the current ocellus, with all non-control related circuitry and wiring subtracted.

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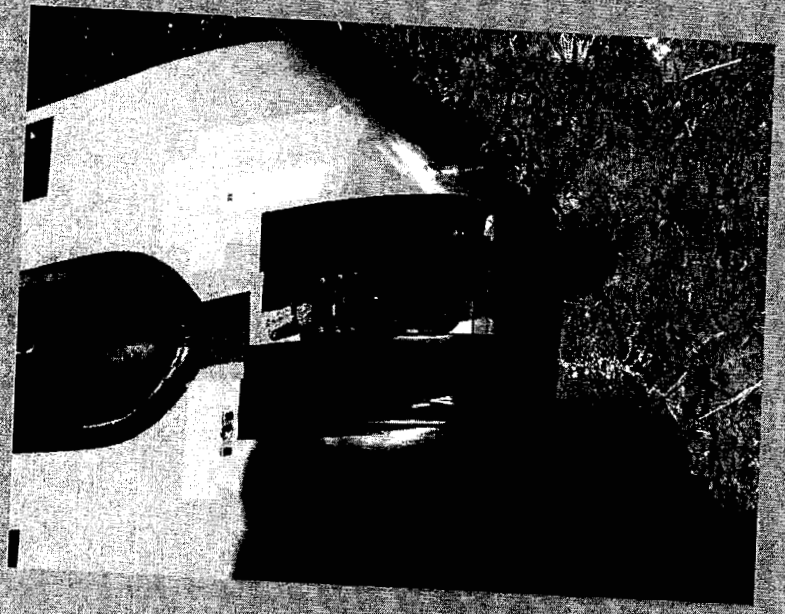
Bioinspired Engineering of Exploration Systems

- Conceptualized innovative use of COTS optical mice part to implement onboard an embedded optic flow sensor for the 1 Kg biomorphic flyer



http://www.labs.agilent.com/news/2001features/fea_optinav.html

J. M. Morookian, J. Chahl, and S. Thakoor (in prep)

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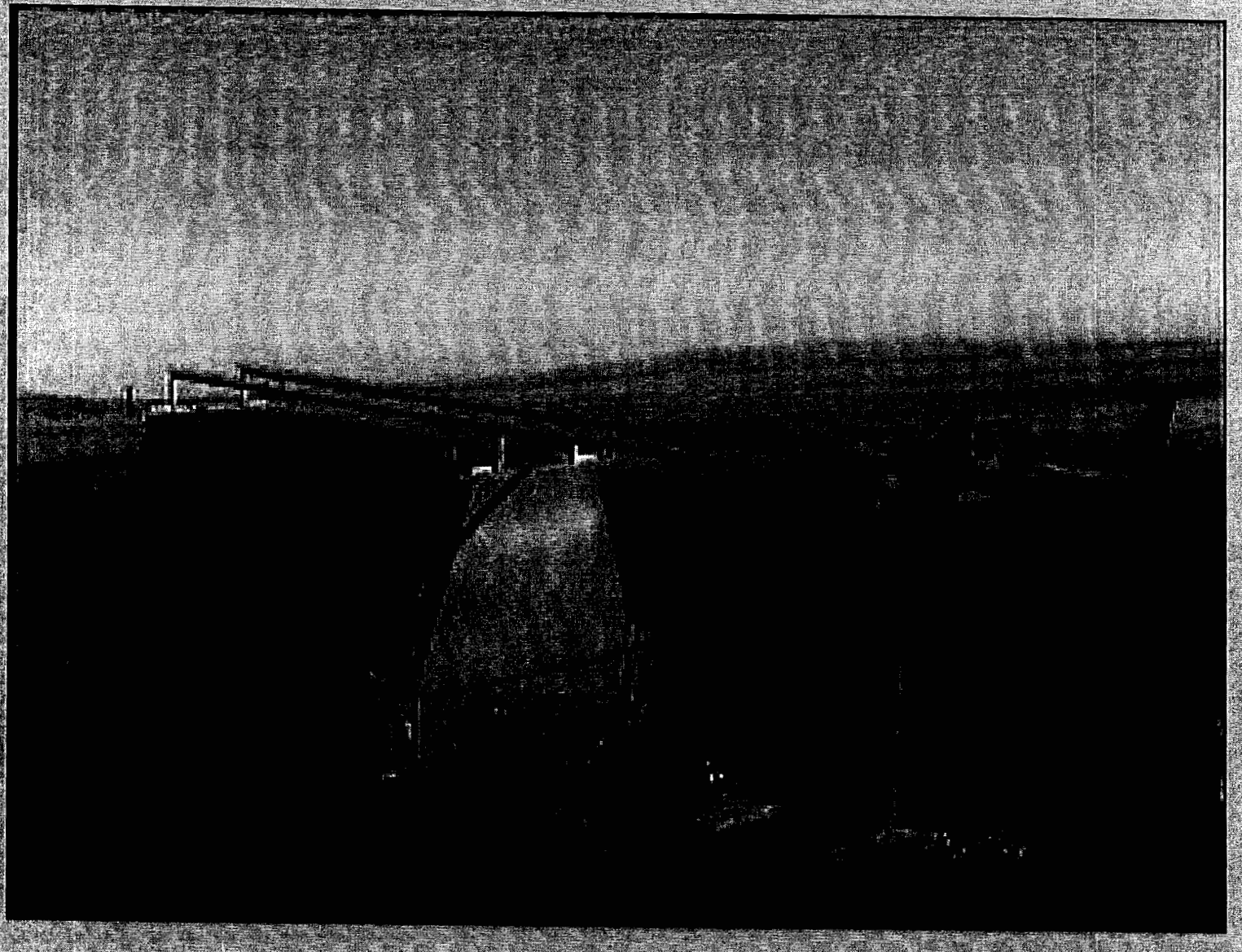

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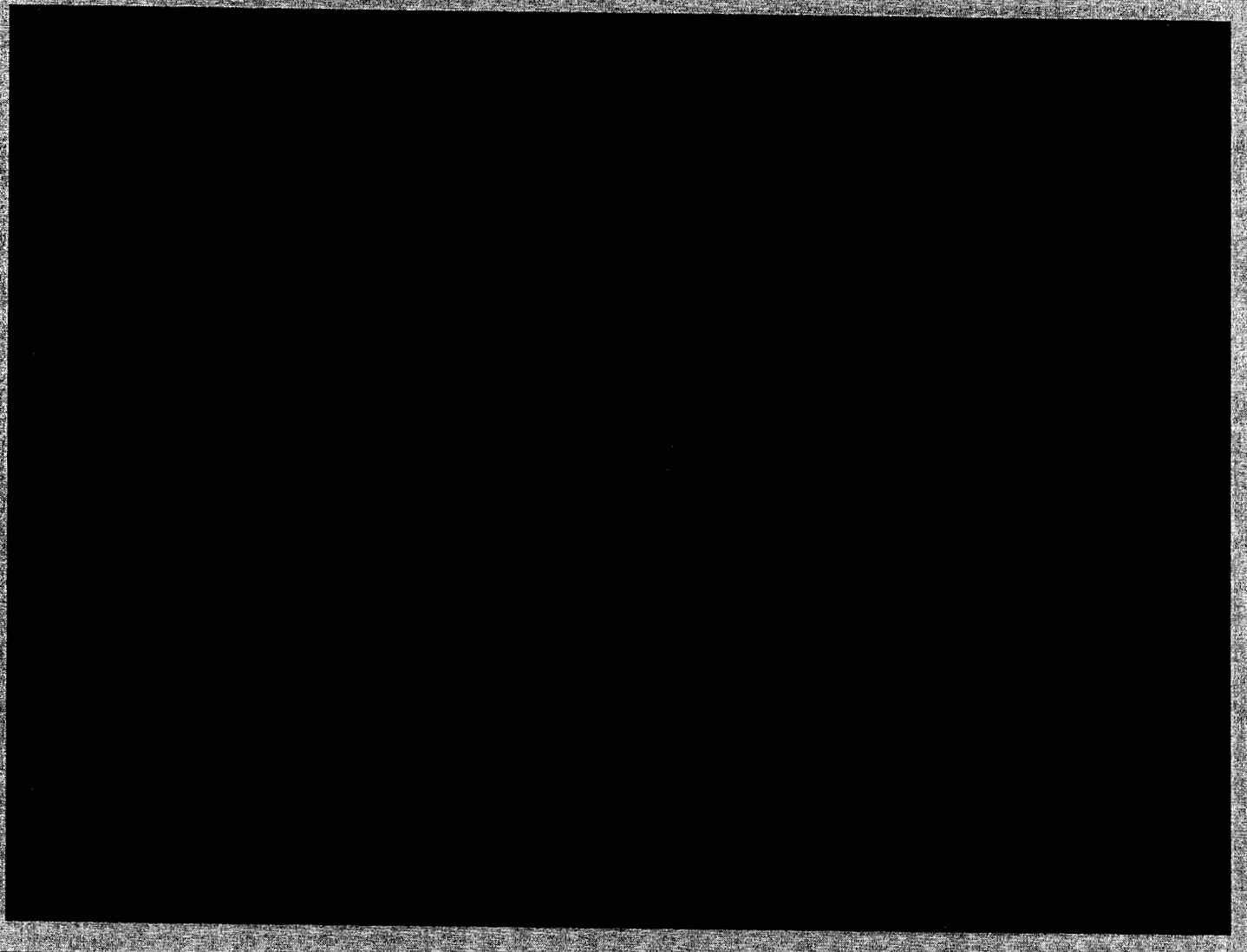
BIOMORPHIC FLYER (5Kg) PROTOTYPE



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Optic flow based control of height above ground

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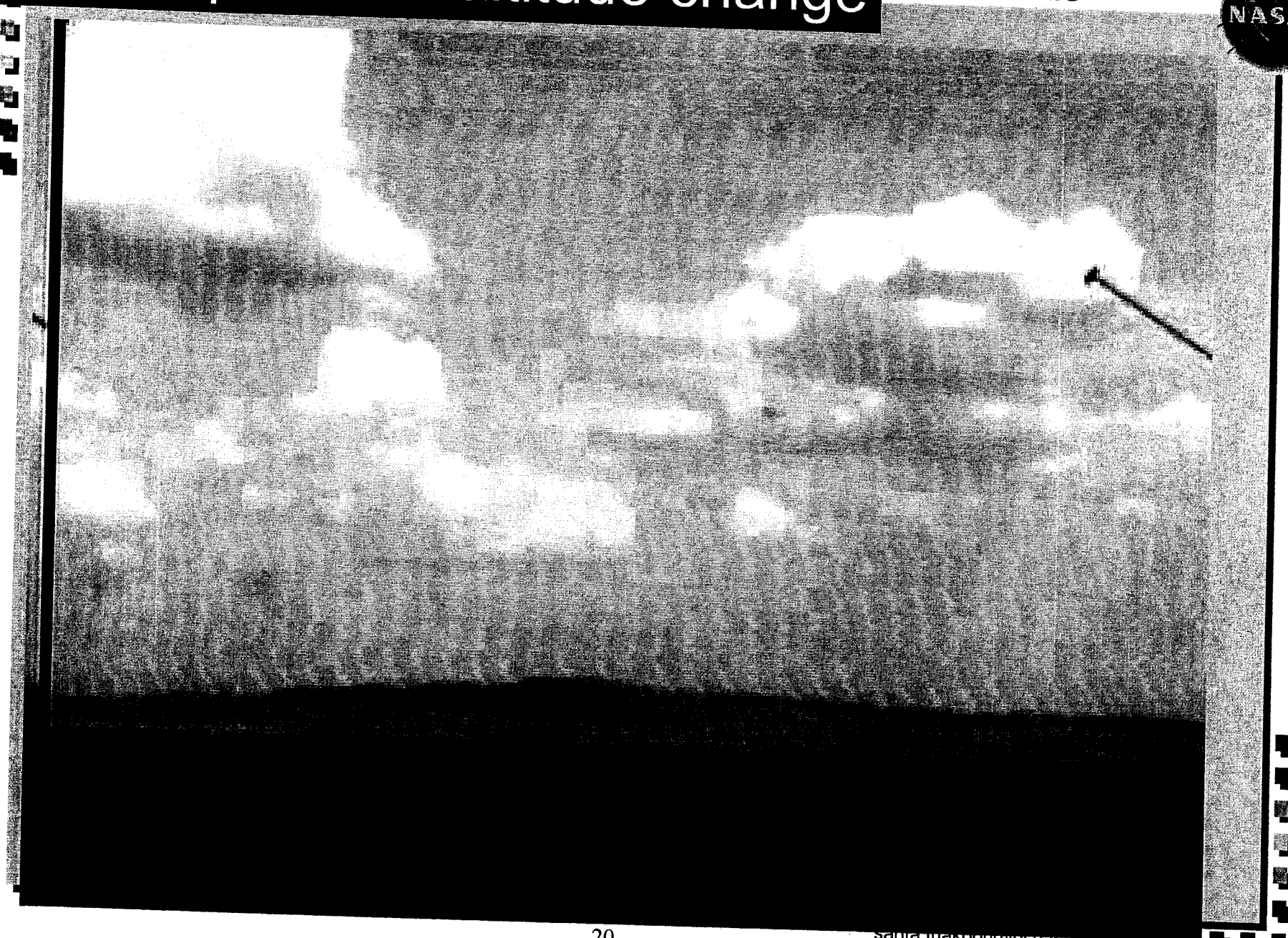
Step response to altitude change

ON SYSTEMS



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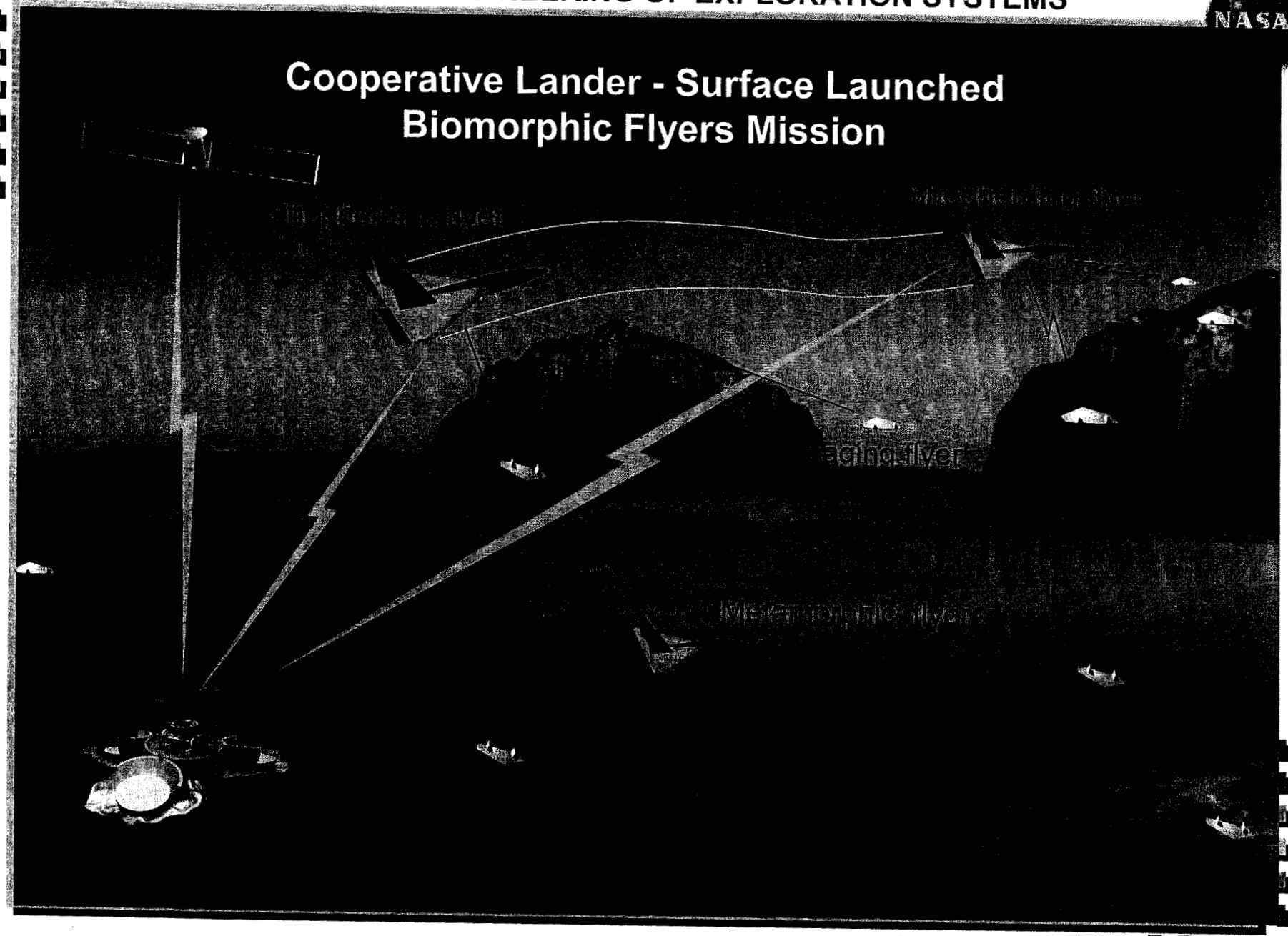
Cooperative Lander - Surface Launched Biomorphic Flyers Mission



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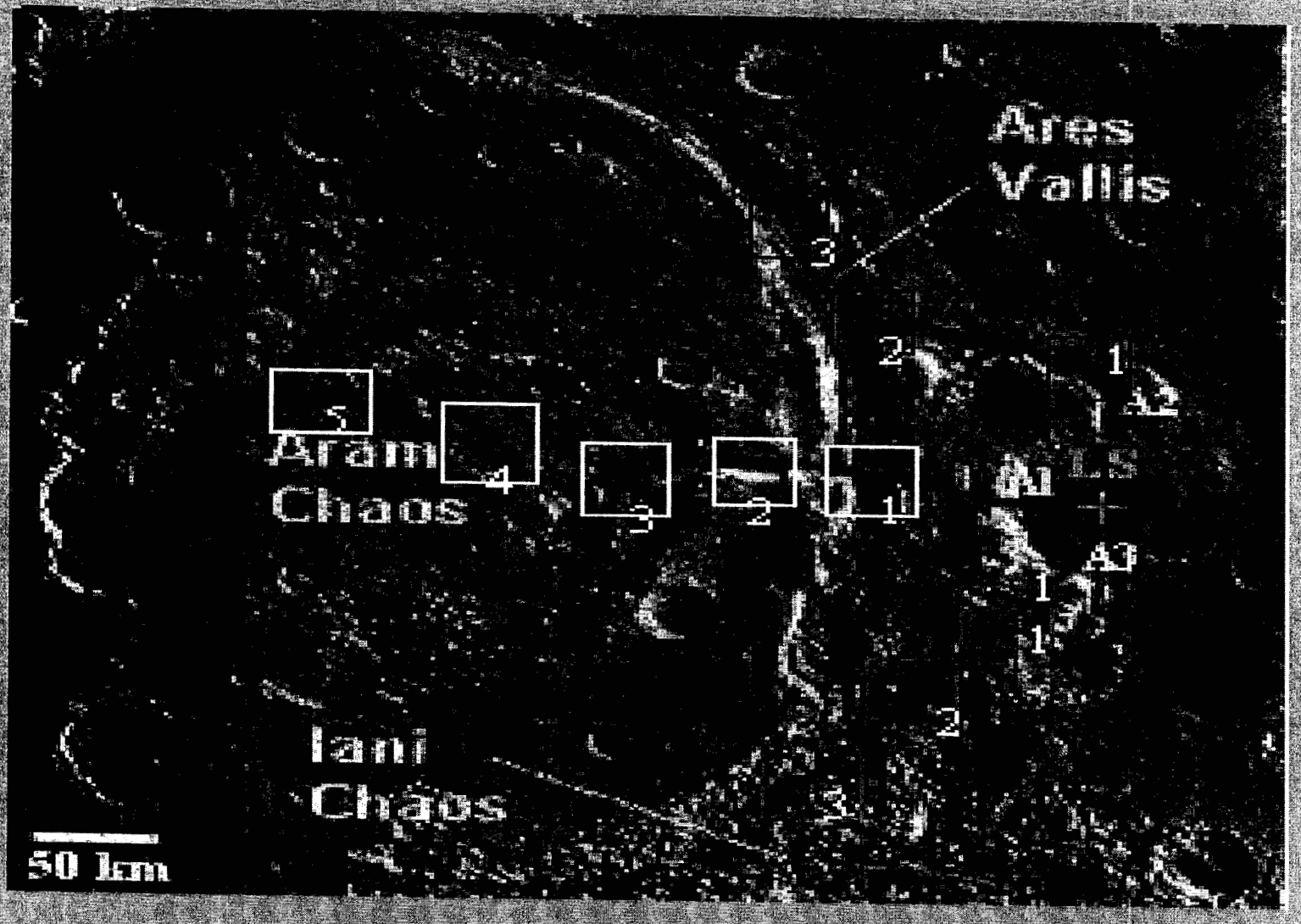

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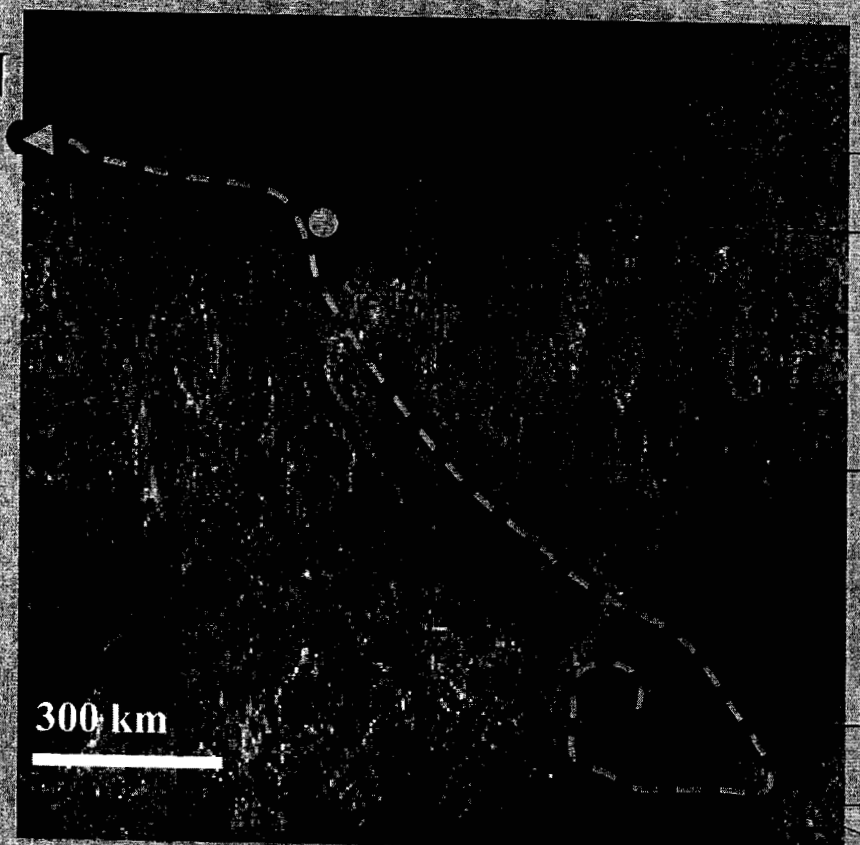
The Case of Aram Chaos



Viking 1: Parent-Rocks? Processes and Changes in 30 years?

Pathfinder Landing Site. Parent-Rocks? Sedimentary rocks?

Ares Vallis: ice, water, clathrates?

Aram Chaos: hematite, delta, high-albedo deposits, ancient water, layers

Source of Ares Vallis/ Chaos

To Hematite Site (0-7W)

Science Advocate: Nathalie Cabrol

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IMAGING and SHEPHERDING FLYERS IN DEVELOPMENT

Item	2001 Biomorphic Flyer Platform 1.5 Kg	5 kg, 2002 -2004 Biomorphic Flyer (Shepherding flyer)	1 kg, 2002 -2004 Biomorphic Flyer (Imaging flyer)
Dry Mass	900g	2670g	600g
Fuel	100g	340g	225g
Payload	427g	1990g	174g
Takeoff weight	1427g	5000g	1000g
Engine	178g	698g	145g
Propellor	9g	58g	8g
Engine Type	OS 15LA	OS 61FX	OS 10LA
Propellor Size	20.3cmx15.2cm	28.0cmx20cm	17.8cmx10.1cm
Top Speed	≈135km/h	≈165km/h	≈110km/h
Landing Speed	≈45km/h	≈55km/h	≈37km/h
Range	25000m	55000m	37000m
Endurance	>12min	>20min	>20min
Wing Span	0.81m	1.240m	0.708m
MAC	0.396m	0.606m	0.346m
Leading edge sweep back	50.8°	50.8°	50.8°
Aspect Ratio	2.206	2.206	2.206
Taper Ratio	0.19	0.19	0.19
Wing Area	0.297 m^2	0.701m^2	0.227m^2
Glide Ratio (L/D)	8.5	8.5	8.5

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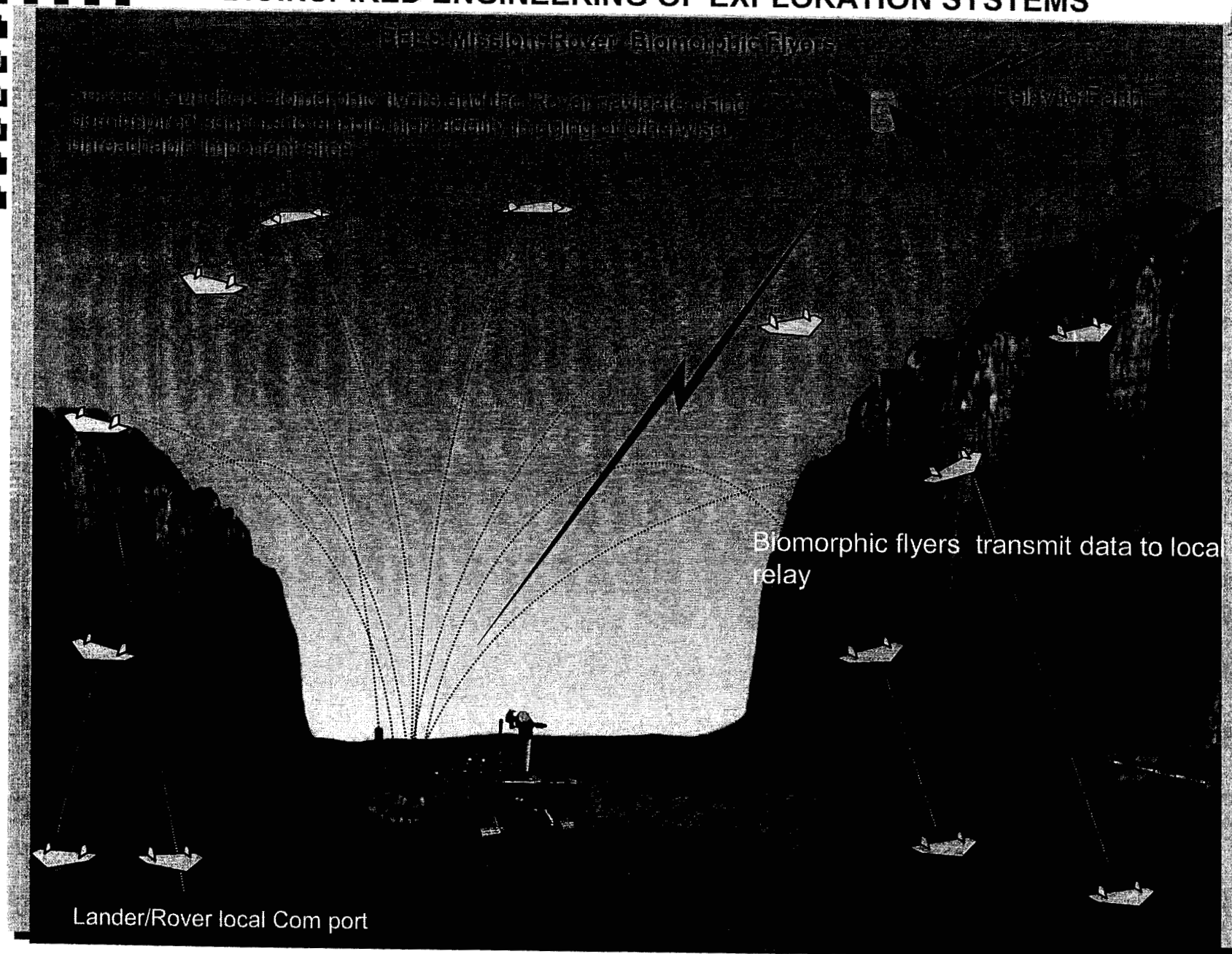

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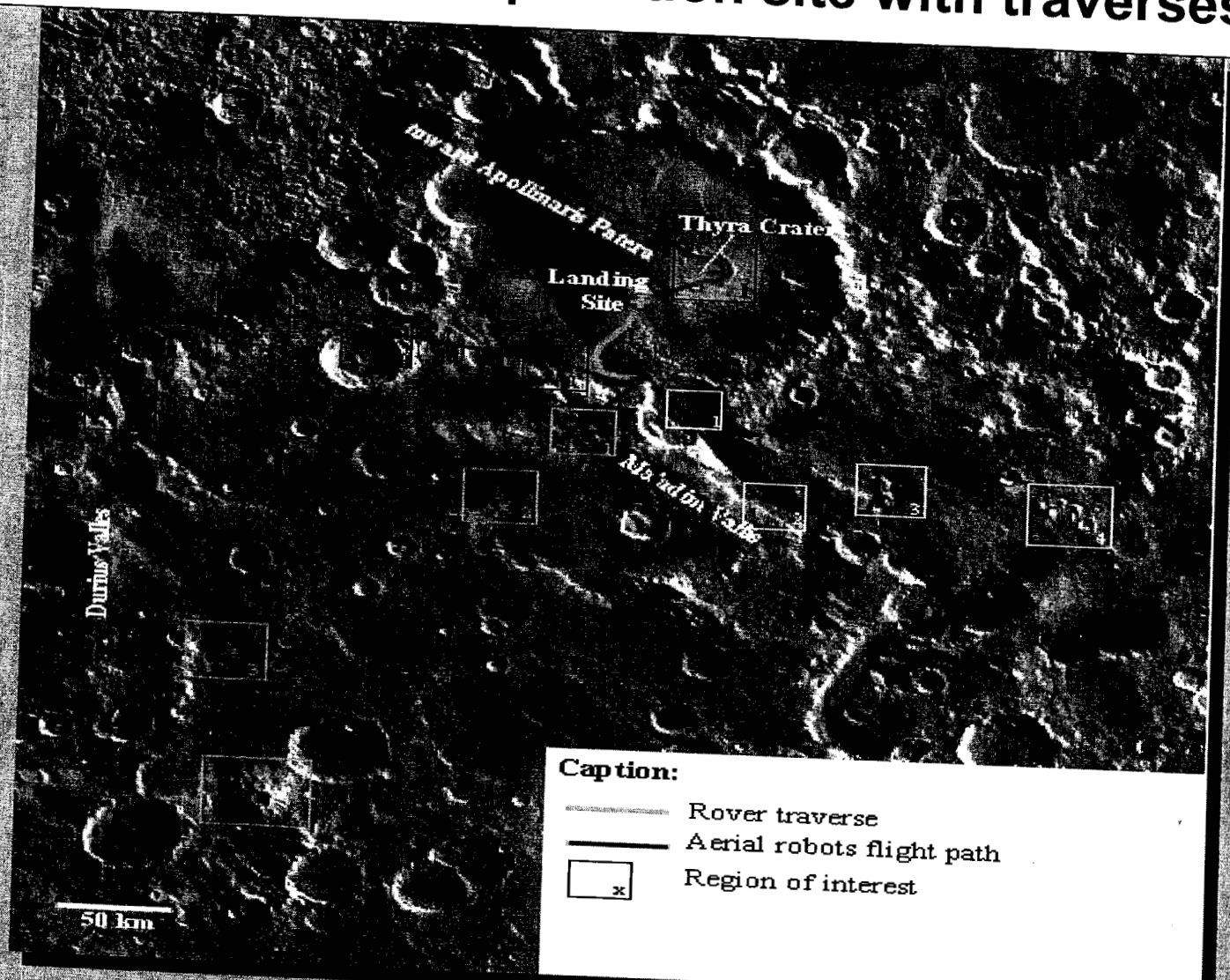
Potential science exploration site with traverses



Science Requirements Courtsey Nathalie Cabrol, NASA AMES

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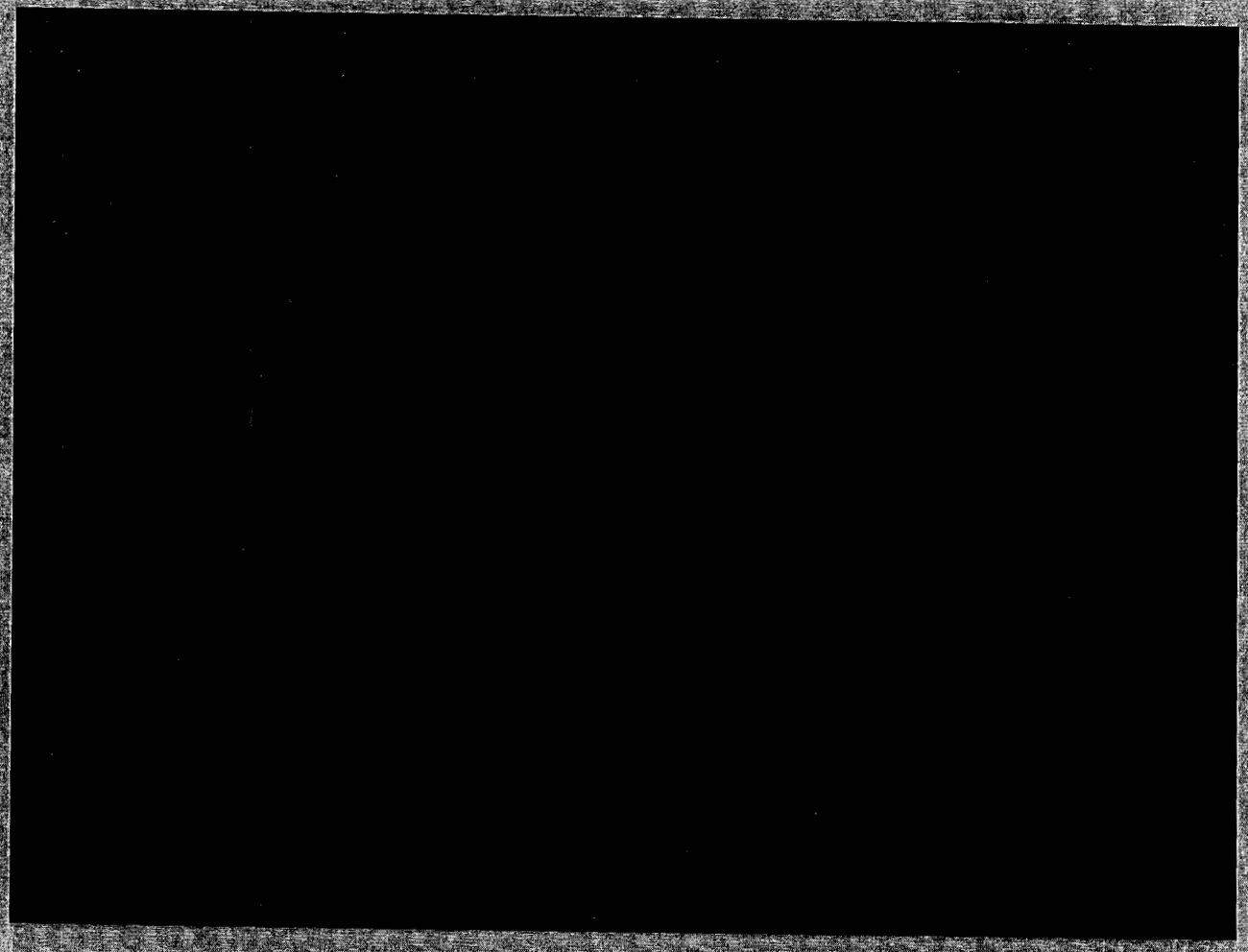
Mars Flyer Animation



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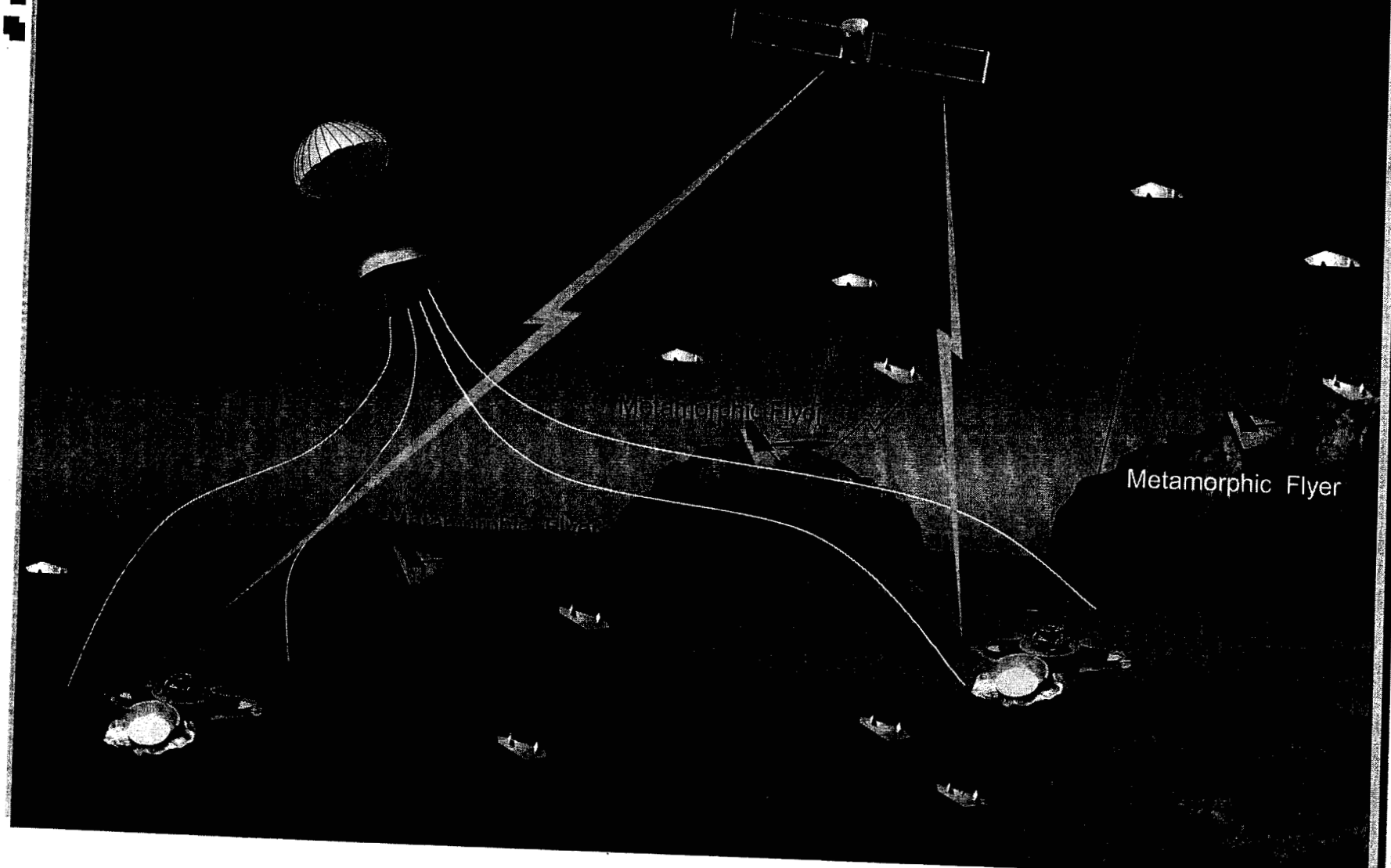
Cooperative Dual Lander Surface Launched Microflyers Mission



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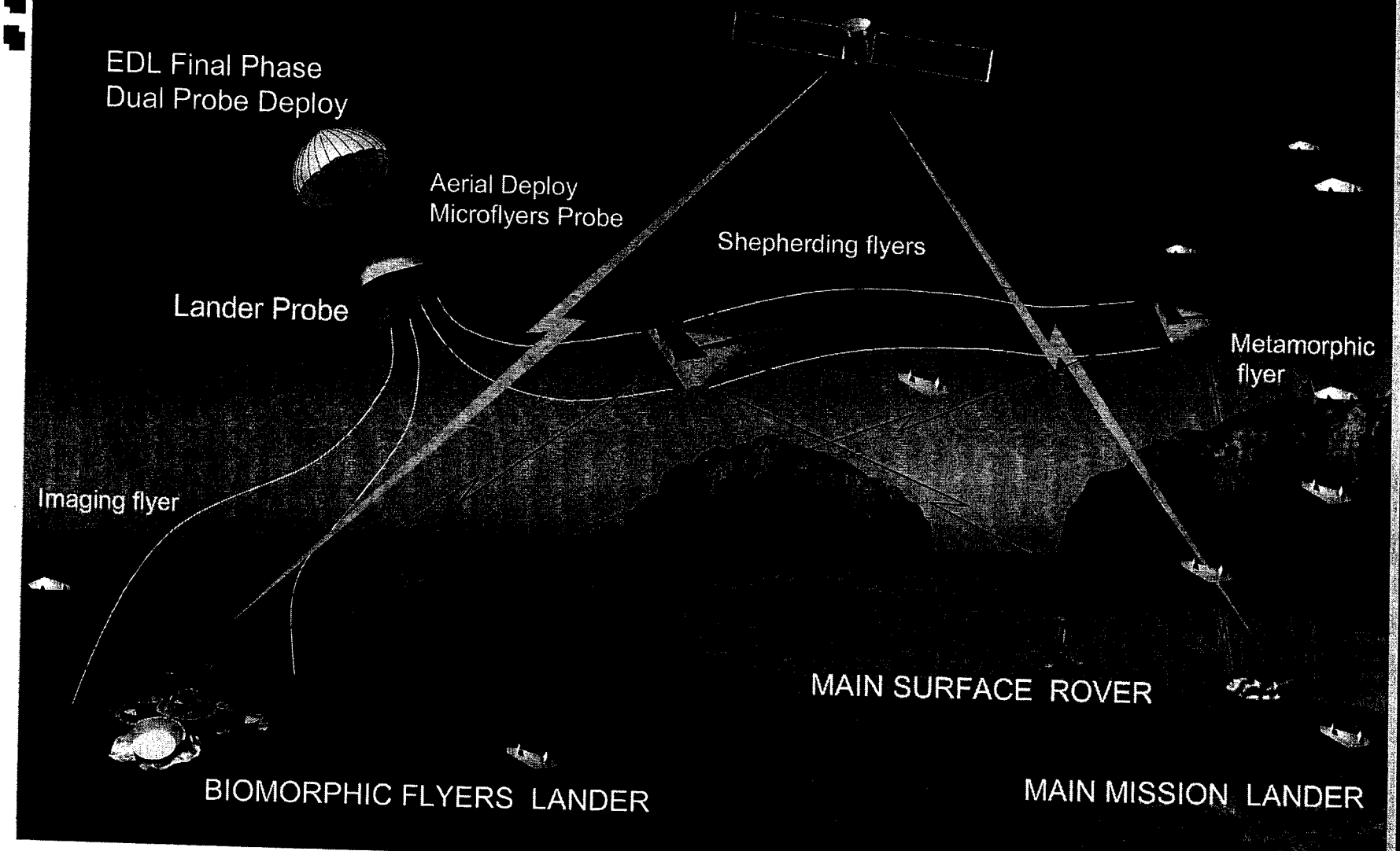
"ENVISIONED BIOMORPHIC MARS MISSION"



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Conclusions

Adapting engineering solutions derived from observing biological organisms to robotic exploration missions can result in increased science return, decreased mission complexity, and increased survivability. The use of mobility, sensing, manipulation, communications, and decision-making strategies that work very well in nature can ultimately result in a huge increase in the amount and quality of the science returned

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CONCLUSION

- By optimizing the BEES sensors and flyers we are well poised to attack the extremely challenging task of visually guided autonomous flight.
- Future work will concentrate on developing the full bioinspired sensor suite (ocellus, optic flow, polarization compass, panoramic camera) and integrating the sensors and controllers.
- We hope to be able to re-scale the aircraft to less than 0.4m wing span with a full autonomy payload.
- The development roadmap is geared towards enabling a BEES Mars Mission in 2009 timeframe and possibly a piggy back of the BEES sensors even before.

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