SUB-KILOGRAM INTELLIGENT TELE-ROBOTS FOR ASTEROID EXPLORATION AND EXPLOITATION (SKIT)

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ABSTRACT

Given current miniaturization trends in robotics, AI, and communications there is now an opportunity to plant "seeds in space." These "seeds" would bring a reduction in the enormous cost associated with sending human explorers to distant space objects when newly designed small tale-robots could perform the precursor missions.

In light of this, our project is to investigate new generations of smaller, networked tele-robots, named SKIT's, for exploring the abundant and rich untapped resources of asteroids. We are performing theoretical and hardware/software simulation studies to determine the relative merits of using sub-kilogram robots for this type of work. A typical scenario for this research would be to release a number of vehicles with some communication capability, and with a specialization of functions on a simulated landscape. Humans would control the overall deployment policy but the tele-robots would have some autonomy to deal with obstacles.

This paper is an attempt to elucidate the challenges of robotics for asteroids, detail some proposed solutions and present a plan for simulations.

A unique challenge of this research is to produce substantial results in 1 year's time given the constraint of designing and building devices that are sub-kilogram. Although the requirement of <1kg for each robot puts forth a challenge to previous modes of thinking, it actually allows new modes where we can benefit from high coverage, high full-system-level reliability, and low cost.

Keywords: distributed agents, micro robots, space exploration

1. MOTIVATION

As articulated in the statement, "An Expanded Agenda for SSI", (Space Studies Institute *Update*, Jan/Feb. 1995), there is an opportunity to take advantage of new technology in the areas of robotics, artificial intelligence and communications to plant "seeds in space." The statement also indicates a lack of clear answers as to, "how should the exploitation of critical space material be balanced between planets, the Moon, asteroids and comets."

With the above challenges and opportunities in mind, it is apparent that substantial research should be conducted utilizing this novel technology to find answers to the crucial questions of space resources utilization. The benefit of this approach would be a reduction in the enormous cost and complexity associated with sending human explorers to distant space objects when small intelligent tele-robots could adequately perform the precursor missions. Our focus is to develop a strategy for robot-

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SKIT... *(Continued from page 1)*

ics/AI that would accelerate, or better yet, *ignite* the colonization of space, first by robots and later by humans. Our intent is to develop a research program involving actual hardware development to produce prototypes of intelligent miniature telerobots that could later be improved, space-qualified and used in precursor missions for space resource prospecting, mining and manufacturing. In addition we have focused our attention on the effective utilization of the abundant and rich untapped resources of asteroids. Our basic goal in this research is to develop a robotic strategy to allow adequate asteroid exploitation in an effort to spark human attempts at the graceful, effective colonization of space. We view the flow of events proceeding in such a way that scientific exploration would lead to prospecting.

Prospecting would lead to the extraction of raw materials, the refining of ores and the eventual desire to build structures to support human habitation.

Our plan is to study the relative merits of miniature size robots, with various degrees of intelligence for the initial phase of this process. We feel precursor missions provide the most cost effective path for colonization, utilizing tale-robots constrained to 1-10 cm in size and 100 gm to 1 Kg in mass. The leverage these constraints may provide are substantial benefits in the areas of reliability, high coverage and low cost. This work is an attempt to investigate a new generation of smaller, intelligent, cooperative, tale-robots, *"SKITs"*, for exploring and possibly exploiting an asteroid's surface. Basically, the plan would be to arrive at a target asteroid and release a number of small vehicles with some communication capability and with a specialization of functions. Humans would control the overall deployment policy and provide broad navigation directions, but the tale-robots would have some local autonomy with respect to handling obstacles.

The advantages of lowering overall system mass are several. The first being that launch vehicle capabilities become less of a constraint. Secondly, small systems usually represent less of an investment. Thus one could expect more missions to be launched or more spacecraft launched per mission. This would provide a steady flow of scientific data that would then parallel scientific laboratories on Earth where a continuous series of experiments are conducted. The current long time span of large missions requires a scientific team to invest a significant fraction of their careers in the hopes that a particular mission will get funded, launched, reach the target and be rewarding. Finally, small systems can go places where their larger cousins are not allowed due to high economic risk or physical geometry. They can also be used to blanket an area to provide nearly continuous sampling in space and time.

We decided to concentrate mostly on asteroid resources due to their proximity, access, quantity and richness. When looking at their proximity and access qualities, it is interesting to note that asteroids represent potential material resources with smaller delta V requirements than needed to deliver resources from the lunar surface to orbital rendezvous. The estimated number of asteroids has been significantly increased in recent years, from a few derelict pieces outside the orbit of Mars, to a vast amount, ~300-500 thousand, in near-Earth orbit with many in the 1 Km range. While these objects so close to Earth can be viewed as hazards, they also represent a massive storehouse of prime elements needed for the eventual colonization of space.

2. INTRODUCTION

Research such as this requires the synergistic and creative use of techniques taken from several disciplines to overcome difficulties arising from working in space. In addition, a good understanding is needed about the environment where we propose our units will function. For this reason this paper is broken up into three parts that cover: 1) the current knowledge about asteroidal environments and their challenges to robot architectures, 2) some proposed designs to overcome these challenges and 3) some current and future simulations being performed to test the proposed designs.

3. CHALLENGES OF THE ASTEROIDAL ENVIRONMENT

This section provides a brief overview of asteroid properties, their environment and a summary of the challenges and hazards from working on them. Since this research is focused on the use of asteroids that come relatively close to the Earth (the so called Apollos, Atens, Amors) more emphasis is given to them.

3.1 Asteroid Parameters

Asteroids, also called minor planets, are rocky objects in orbit around the Sun. Most asteroids orbit the Sun between Mars and Jupiter, moving in the same direction as the planets. Asteroids range in size from Ceres, which has a

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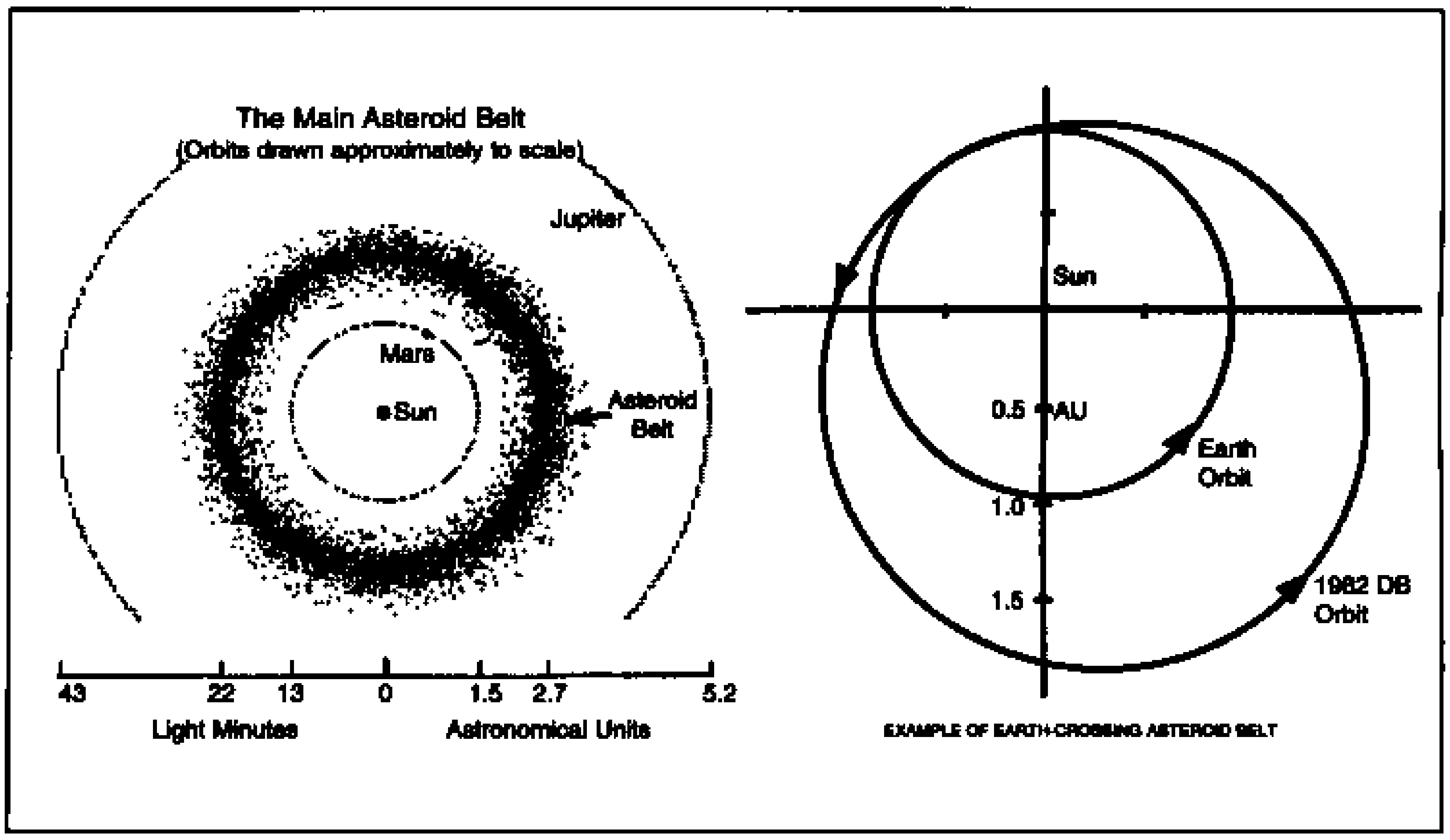


Figure I. Asteroid Orbits
A) The Main Asteroid Belt (Doody, 1995) *B) 1992DB Earth Crossing (Chatterjee, 1988)*

SKIT... *(Continued from page 2)*

diameter of about 1000 km, down to the size of pebbles. Some asteroids, called Apollo Asteroids, cross the orbit of Earth. It has been estimated that there are around 1500 Earth-crossing asteroids with a diameter of a kilometer or more. Around 300 of these have been found as of June 1996 and many more are added to the list yearly.

The asteroid belt, home of most asteroids, lies between the orbits of Mars and Jupiter. The chart (Figure 1, A), put together from Spacewatch observations, shows that smaller asteroids produced by fragmentation of the larger ones, are more numerous. The rocks normally remain in circular, stable orbits, but collisions along with the gravitational influence of Jupiter, can throw them into narrow, unstable orbits. The asteroids sometimes enter the inner solar system, where they come close to Earth. Asteroid 1982DB (Figure 1, B) is an example of this type of perturbation and resulting orbit.

Aten, Apollo and Amor Asteroids

A group of planet-crossing asteroids, the Aten, Apollo and Amor Objects (AAAO) have orbits carrying them outside of the main asteroid belt. The Atens are defined as asteroids having a semi-major axis less than that of the Earth (1.0 AU). The Apollos, by definition, have orbits that cross that of the Earth. The Amors approach the Earth, passing inside the orbit of Mars but not inside of the Earth's orbit. (Shoemaker et al., 1979) estimate that the population, consists of approximately 100 Atens, 700 +/- 300 Apollos, and 1000 to 2000 Amors, although the total number of known objects is currently in the 100's. The close proximity of AAAO to the Earth makes them remarkable both for their potential usefulness for space-borne activities (habitation and manufacturing) and their possible destructiveness resulting from collisions with the Earth. The population of planet-crossing asteroids appears to be extremely diverse in all aspects of their physical properties.

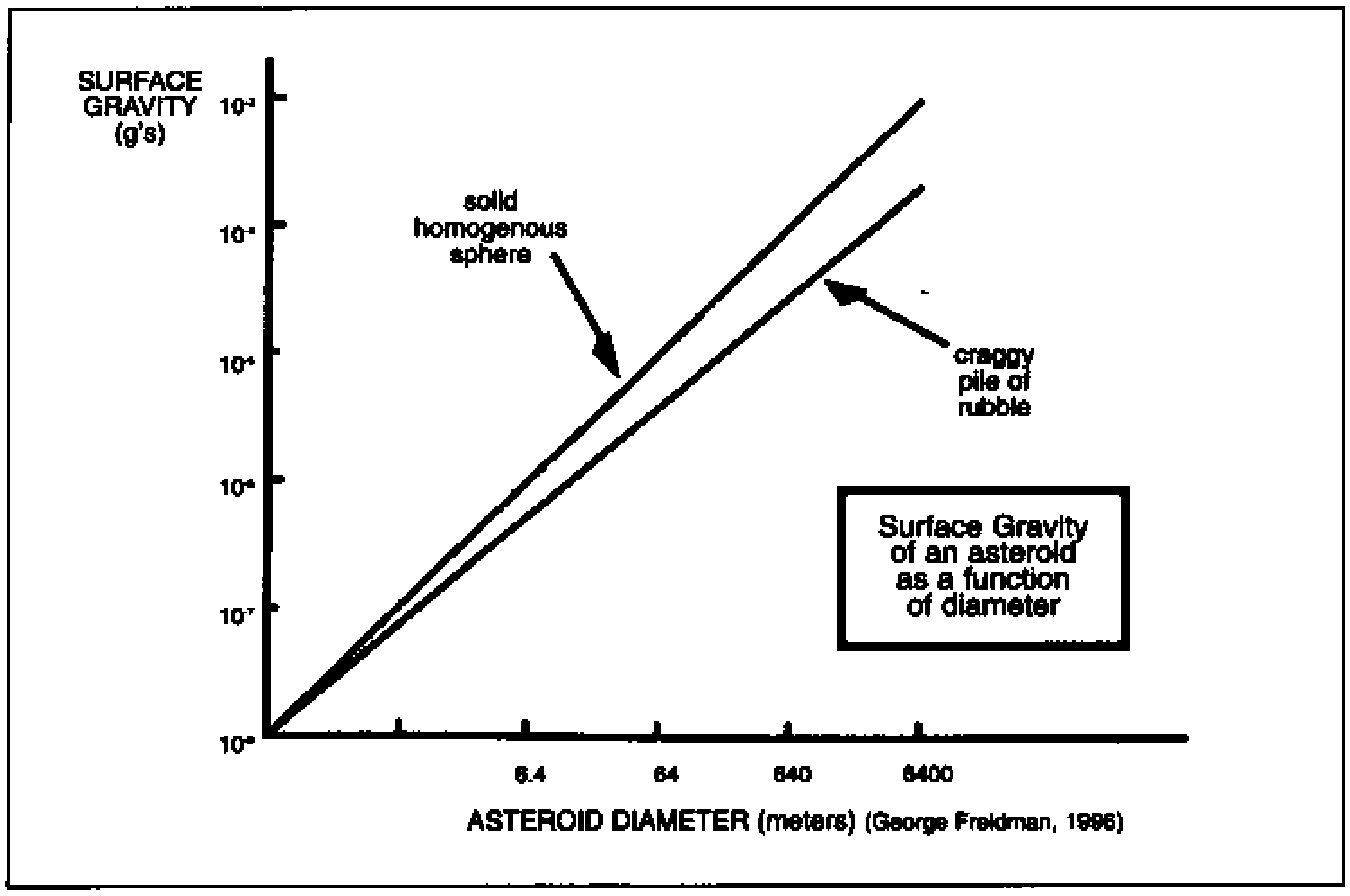
3.2 Asteroid Environment

The conventional environments currently put forth are arrived largely through the study of meteorites, theoretical studies of the orbital dynamics of the solar system, ground-based observations of the asteroids and some space-based observation. If the scientist's predictions are correct we should find that most of the asteroids are covered with regoliths — several kilometers deep on the largest, and thin, or absent, on the smallest. The asteroids will probably have major internal fractures, and may show linear striations not unlike those found on Mar's satellite, Phobos. In their interiors we should find that the C-type objects are fairly homogeneous and undifferentiated, while other types will have a layered, differentiated interior, or a spotty, raisin bread structure. Some asteroids should prove to be the stripped cores, or the outer fragments, of differentiated asteroids which were destroyed in massive collisions. More importantly, it is hoped that upon examination it is found that the mineralogical compositions that have been inferred are correct, such as: C-asteroids are carbonaceous, S-asteroids are silicanceous and M-asteroids are metallic. But it is far from certain that these inferences are correct (Kowal 1992). The following sections describe each of the areas mentioned here in further detail.

Shapes, Mass and Density

The shapes of small asteroids are probably irregular if they are collisional fragments. They usually have one axis that is relatively greater than the other. All available photometric and radar measurements model the AAAO as non-spherical objects except for 1566 Icarus. This small (0.9 km) asteroid is apparently close to being spherical (Gehrels, 1996). Currently there are several ways of determining diameters of the asteroids, but the determination of mass and density are much more difficult. To get density you must know the volume and mass. The only way to determine mass is to measure the gravitational effect of one object to some other body. A good way to do this is to send a probe and measure its effect (Kowal 1992). Since this has not been done our understanding of asteroid masses comes about from speculation and study of meteorites and asteroid evolution theories. Thus, there is still much uncertainty about asteroid densities. To give an example of this unknown, in a related mission to a comet, engineers were asked to design a subsurface sample acquisition device but the best value agreed upon by current studies put the comet's density at somewhere within three orders of magnitude.

A result of the small mass of asteroids is depicted in Figure 2. The implication is that care must be taken when designing propulsion devices so as not to inadvertently lose contact with an asteroid. In a different light, (Shoemaker, 1977), made the statement that "Because impulses for landing and



(George Freidman, 1996)

Figure 2 Surface Gravity vs. Asteroid Diameter

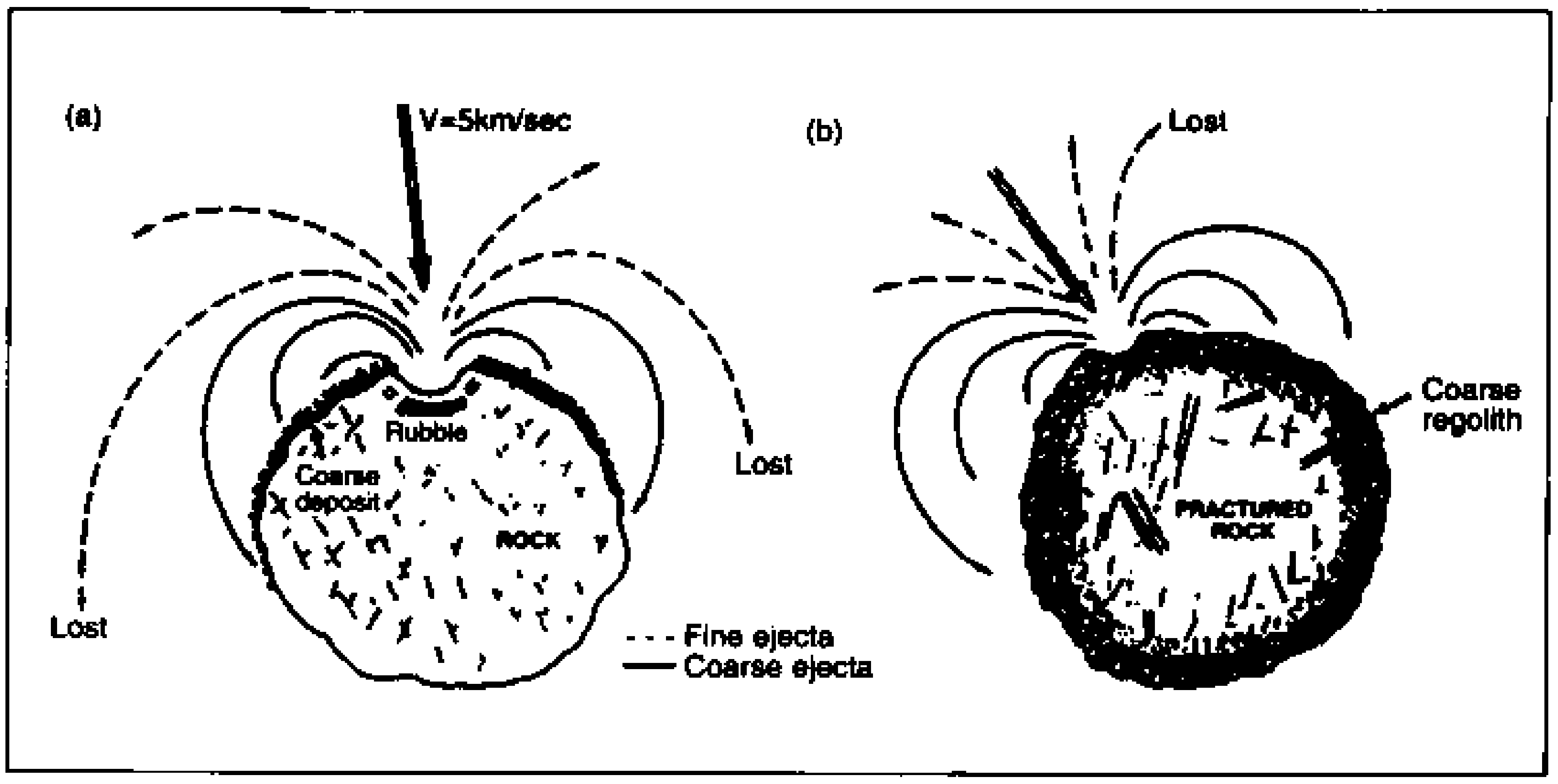


***Figure 3** Formation of the regolith at the surface of an asteroid.* *(Figure adapted from Dollfus 1986)*

escape from these small asteroids are of the order of Im/sec, many landings could be made to visit and sample different parts of an asteroid in the course of a single mission." This statement opens up a multitude of possibilities for novel mission and robot vehicle designs.

Surface Properties

Our present understanding of the surface topology and structure of asteroids is very poor. It is believed that an asteroid's surface is covered by many craters, has a craggy surface and each has a certain amount of regolith depending on its diameter. Regolith is the term for small particles or sand when found in an extraterrestrial body. There is evidence, from both radar and photometry, of heterogeneity across the surface of some AAAO. Radar (Goldstein et al. 1981) and radiometry (Lebofsky et al. 1981) measurements of 1862 Apollo support a modeled dusty-regolith surface for this asteroid. Polarimetric measurements for 1862 Apollo also support independent data indicating that this km-sized body has a dusty regolith. The formation of the regolith at the surface of an asteroid is shown in Figure 3. In (a) low-velocity meteoroid impacts (typically 5 km s~l) eject coarse fragments at low velocity, which return to the surface, and small dust grains at a velocity higher than the escape velocity are lost into space. In (b) an accumulation of such ejecta ends up as a thick layer of coarse fragments while the smaller grains disappear into space. If current theories are correct most of the asteroids are covered with regolith — several kilometers deep on the largest, and thin, or absent, on the smallest due to the gravitational attraction to these small particles.

3.3 Challenges of the Aten, Apollo and Amor Asteroids

The physical properties of Aten, Apollo and Amor objects including their taxonomy, composition, size, rotation rate, shape and surface texture, are derived from observations using spectrophotometry, reflectance spectroscopy, broad-band photometry, radiometry, polarimetry and radar. Our current understanding of this population is that it is diverse in terms of all physical properties that can be studied from the ground and consists of contributions from more than one source region. Almost all taxonomic types found in the main belt are present among this population. Most AAAO have been modeled as spherical objects with a variety of surface textures and roughness. There is more diversity in their roughness at the cm-to-m scale than observed among the main-belt asteroids. Furthermore, since typically Near Earth Asteroids (NEA) are small, irregularly-shaped bodies, presumably with similarly irregular gravity fields, navigation and operations in the near-asteroid environment will be substantially more complex than would be the case for Mars or the Moon.

Table 1 gives a summary of the attributes of working on the surface of a near-Earth asteroid. Of special note are the three parameters of *Temperature, Gravity* and *Liotation Rate.* They tend to be the most influential when considering the best alternative from several solutions. The final parameter, *Uncertain Asteroid Properties,* is also a key driver by having the effect of forcing designers to create systems that must perform in environments where properties are not known within orders of magnitude.

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Parameter	**Effects**	**Results**
Temperature Diurnal temperature swings (50-430K)	Embrittlement, Lubricant efficacy Thermal Stresses Possible need for thermal control	Mechanism Failure Motor Lockup Elect. Interconnect Failures
Gravity Gradients Weak Field (`.003m/sec^2)	Range of gravity's due to rotation and shape Low attractive properties	Mechanisms must move slowly or be self-righting Low escape velocity
Chemicals/Minerals in Soil Fines Magnetic Fines Oxidants/Acidic	Accelerated wear, caking Attraction to magnets Thermal insulation, abrasion Corrosion	Mechanism Failure Motor Lockup Elect. Interconnect Failure Mechanism Failure
Terrain Small Diameter (1 Km) Craggy surface Possible deep or no regolith	Short distance to horizon Jagged cliffs and valleys Contamination of optics and solar cells	Difficult path and comm. Non-linear traversal Entrapment, Obscuring
Distance To Earth Inclination	Comm. traversal distance Difficult comm. viewing angle	Communication time lag Short comm. windows
Rotation Rates (1-1000 hr)	Effect on insulation Effect on Earth viewing time	Power starvation wide thermal cycles Stalls between comm. links
Vacuum Atmosphere	Lubricant efficacy	Motor/Mechanism Lockup
System Lifetime Requirement	Time effects on materials	Part wear-out
Uncertain Asteroid Properties	Range of values on parameters	Difficult design process

***Table 1** Asteroid Environmental Challenges* *(Case given for an Asteroid of 1 Km diameter at 1 AU from Earth)*

SKIT... (Continued from page 5)

3.4 Asteroid Objectives

The primary scientific objectives for asteroids is imagery and a detailed determination of their composition. These diagnostic elements should be measured with sufficient global coverage to determine the scale and extent of chemical heterogeneity. In addition, in order to get samples that are pristine a drill or some other tool will be needed. The following list is an example of the most important properties for determining the future use of near-Earth asteroids.

Bulk properties	Size, shape, volume, mass, gravity field and spin state
Surface properties	Elemental & mineral composition, morphology, texture
Internal properties	Mass distribution, possible magnetic field
Environment	Possible near-asteroid gas and dust, solar wind interaction

Science payloads useful to determine these properties are:

Essential instruments	Imager (CCD) Gamma or X-ray spectrometer Radio science package
Highly desirable, but not essential	IR radiometer Magnetometer
Other useful instruments	Penetrator Dust collector/ analyzer Mass spectrometer

The next section describes some techniques sought to overcome some of the challenges and provide functionality to perform the required objectives stated above.

4. SKIT COLONY ARCHITECTURES AND TASK BREAKDOWNS

The largest difficulty of working in a very low gravity environment is overcoming the problem of undesired reactive motions. In adherence with the conservation of momentum, an actuator that moves an arm in one direction will also move the body of robot in the opposite direction. Furthermore, a small push against the surface for mobility or otherwise may result in a slow journey away and then back to the surface at a location that is difficult to predetermine. On these types of small bodies the effective gravity will not provide an assured natural anchor to the body and the ability to ignore most reactive motions.

The following section starts by describing three different strategies proposed to overcome some of the difficulties of low-gravity environments while providing a method of performing measurements and work at several distant places on the surface of an asteroid. It concludes with structure to detail the way tasks can be broken down for a SKIT system.

4.1 SKIT Colony Architecture Strategies

The three concepts described in this section show several methods SKITs can be organized depending on the tasks desired. First a general description and diagram is given, then some alternatives are listed and finally pros and cons for each design.

4.1.1 Colony of SKITs

This architecture describes a colony that is centrally delivered to a desired place on the asteroid's surface. Upon arrival each of the SKITs perform a self health check and wait to receive orders as to where to go. These orders will be gathered on Earth after analysis of the descent images taken from the mother spacecraft. The circles represent the area in which each SKIT will work once they have traversed to the desired location.

Alternatives:

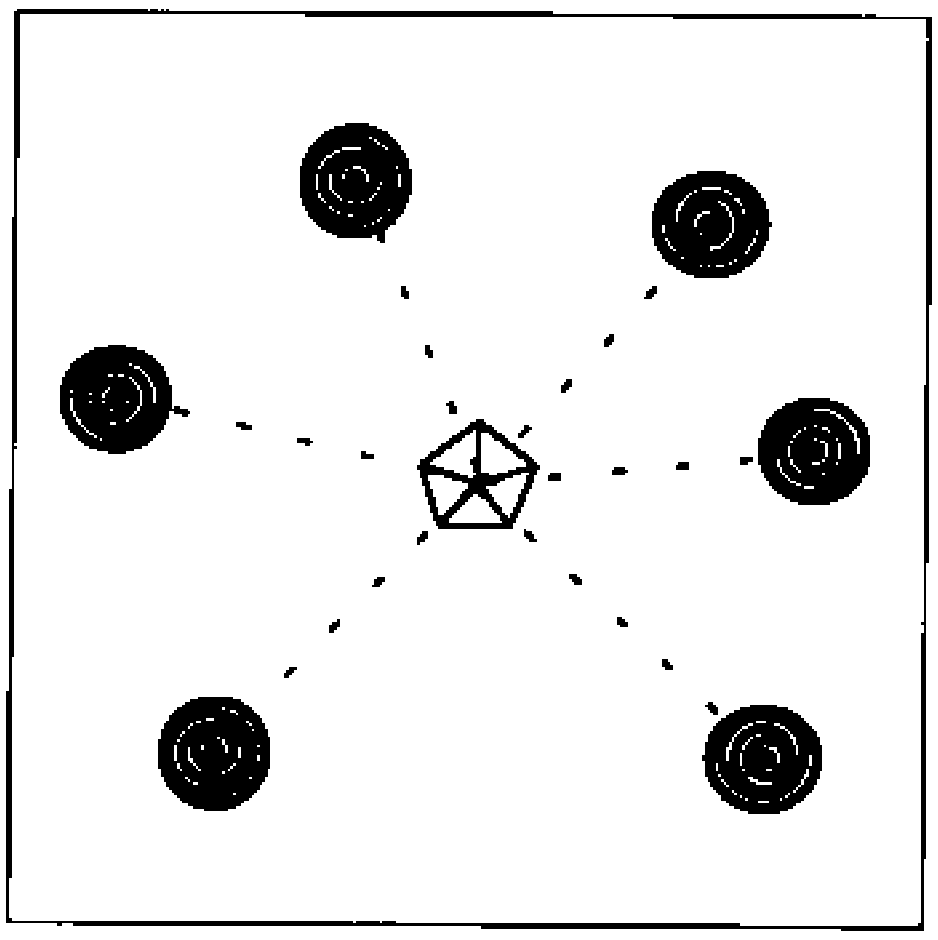
1) System is composed of similar agents that return home for new tools
2) System is composed of heterogeneous agents specialized to specific tasks

Pros:

- Initial location of the mother craft can be controlled for optimal placement
- Single point of arrival alleviates complexities in asteroid rendezvous
- Redundant agents can take over for faulty ones

Cons:

- Difficult traversal to distant areas from initial placement
- Complexities arise during a return to mother craft for tool change or resupply
- Initial setup may take a long time due to distances and terrain difficulties
- Possible single point of failure if the mother craft doe ; not function



SKITs traverse to/from a central base

4.1.2 Network of SKITs

This architecture describes a group of SKITs separately delivered by the cruise spacecraft a distance (~10 km) from the asteroid to a desired place on its surface. Upon arrival each SKIT will perform a self check and begin network initialization by determining other SKITs it can reach via wireless radio transmissions. After completion of the auto configuration of the communication network SKITs can begin performing experiments and await further commands to be performed. An additional feature would be the ability to auto-reconfigure the network in the event of failures of any of the nodes.

Alternatives:

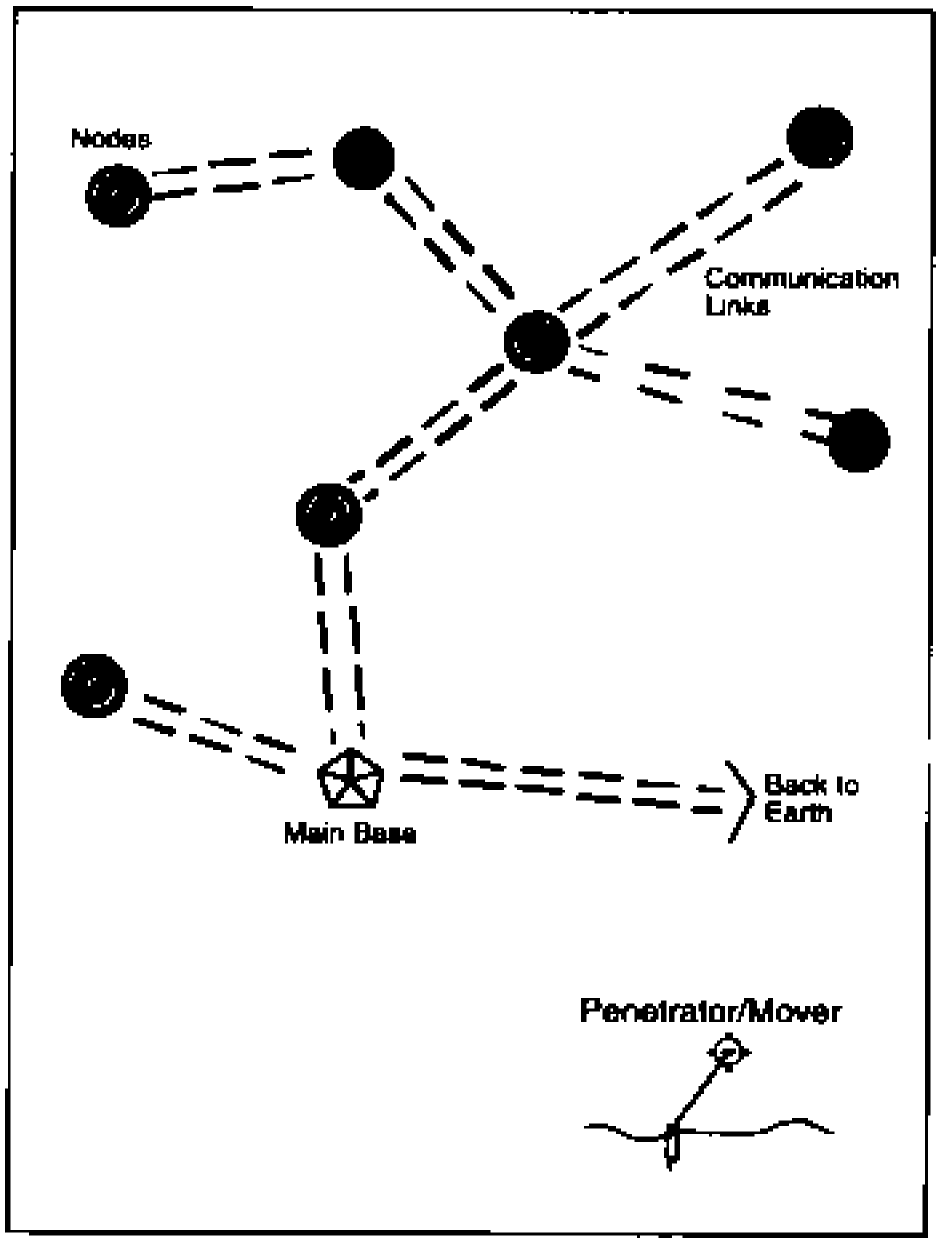
1) System is composed of a network of penetrators
2) System is composed of a network of penetrators/movers. Movers can be hoppers tethered to a penetrating device

Pros:

- Easy access to wide distances from initial arrival
- Low power requirements for communication due to a receive and pass-on network
- Simple mobility systems due to only short traversals needed around arrival site
- Simple arrival since relative velocities (asteroid to SKITs) need not be reduced

Cons:

- Large distances from other SKITs could prevent joint work and failure mitigation
- Designs must survive high G impacts
- Little is known about the efficacy of penetrators for asteroids



SKITs communicate via a wireless network

4.1.3 Net of Agents

This architecture consists of a group of SKITs that are attached to a common net. The net can initially be spun out before arrival or spread out once the SKITs are located on the surface. The net in turn could provide a mechanism for: anchoring, mobility, communications, antenna, power, etc. As shown in the diagram, if the net is designed in a square pattern the SKITs can traverse it in several directions and can also converge for tasks requiring more than one. The attachment points can contain tool, instrument and part stores in addition to providing power generation.

(Continued on page 8)

SKIT... *(Continued from page 7)*

Alternatives:

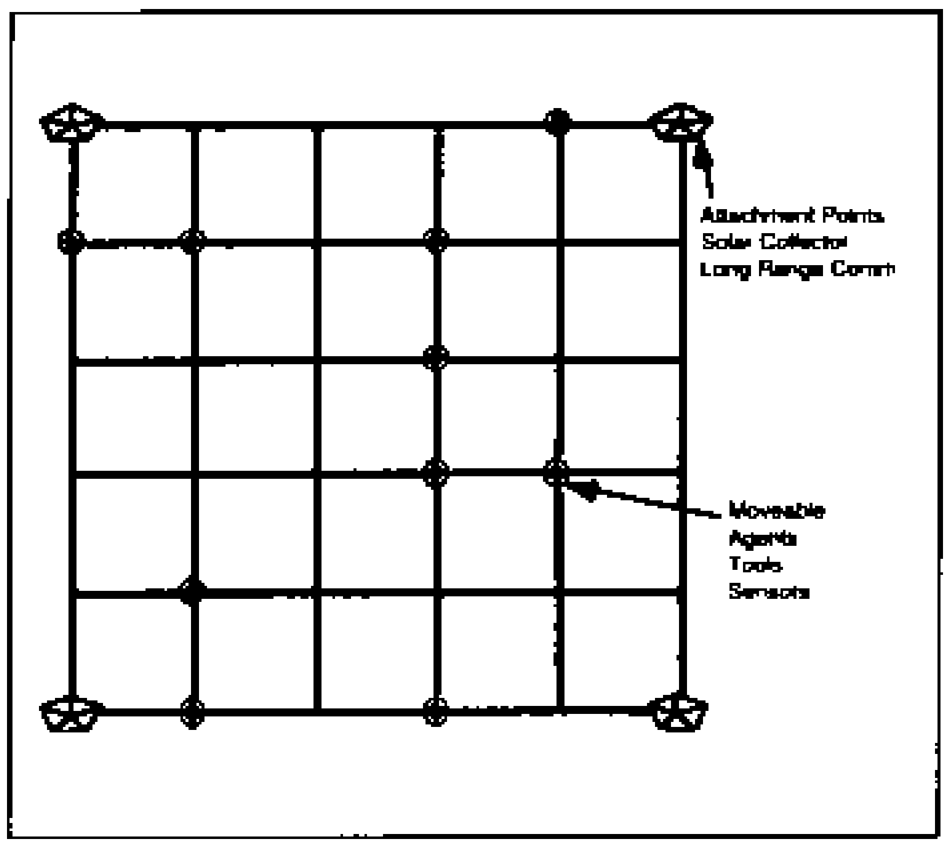
1) Small net of SKITs - relatively small compared to asteroid with attachment points
2) Giant net of SKITs - relative large compared to asteroid, used to entrap entire body

Pros:

- Nets overcome the severe difficulty of traversal & attachment in low gravity
- Nets can provide infrastructure needed to aid SKITs with power, comm., etc.

Cons:

- Unfurling and attachment of net can cause severe complications
- Net connection can reduce traversal options compared to unattached designs



SKITs communicate via a wireless network

4.2 SKITs Tasks Breakdown

The division of labor scheme applicable to a group of SKITs can be varied to suit almost any need. The range of options listed here can be placed on a single-axis graph with *specialized* SKITs at one end and *modular* SKITs on the other. A description of the elements at either end is given in the following:

Specialized SKITs

- Master controller/communicator
- Solar collector/power manager
- Tool kit handler
- Science instrument handler
- Repair technician
- Spare parts handler

Modular SKITs

- Mobile operator
- Mobile batteries
- Micro-watt receiver
- Mobility & Experiment sensors
- Modular Actuator/Hand
- Central Storage

While any point on this graph will have its pros and cons the decision was made to produce a hybrid task breakdown that is more general and can take from the strengths of each end. It consists of a three-tiered colony as described in the following:

1) Home base units are transportable but not necessarily mobile, they perform centralized functions of headquarter's control, power management, tool storage, systems status and parts replacement

2) Mobile workers perform science, prospecting and material handling tasks

3) Mobile helpers deploy anchors and webs, move and hold objects, provide messenger functions and assist mobile workers

It is intended that the above task breakdown structure will be used to guide further research into how SKITs will be designed and what each type will be required to perform.

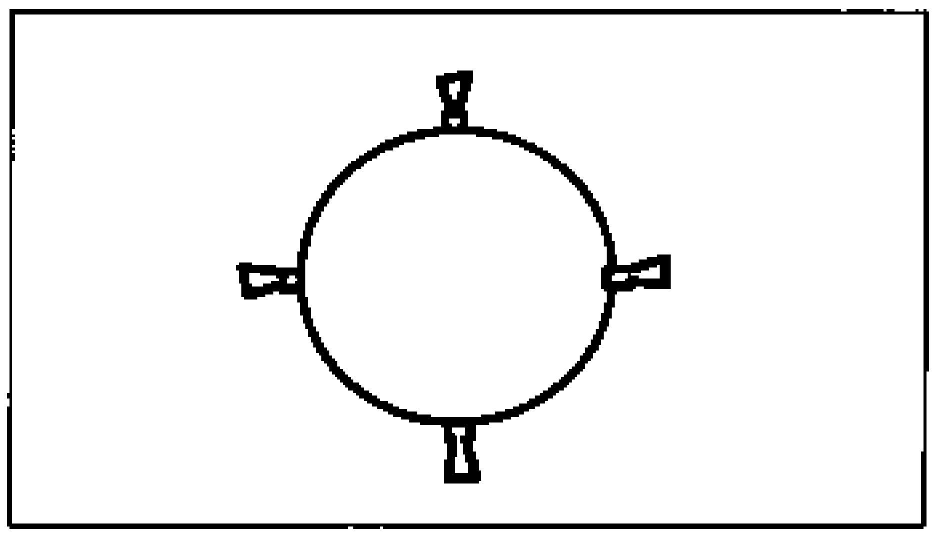
5. CURRENT AND FUTURE SIMULATIONS

5.1 Current Simulations

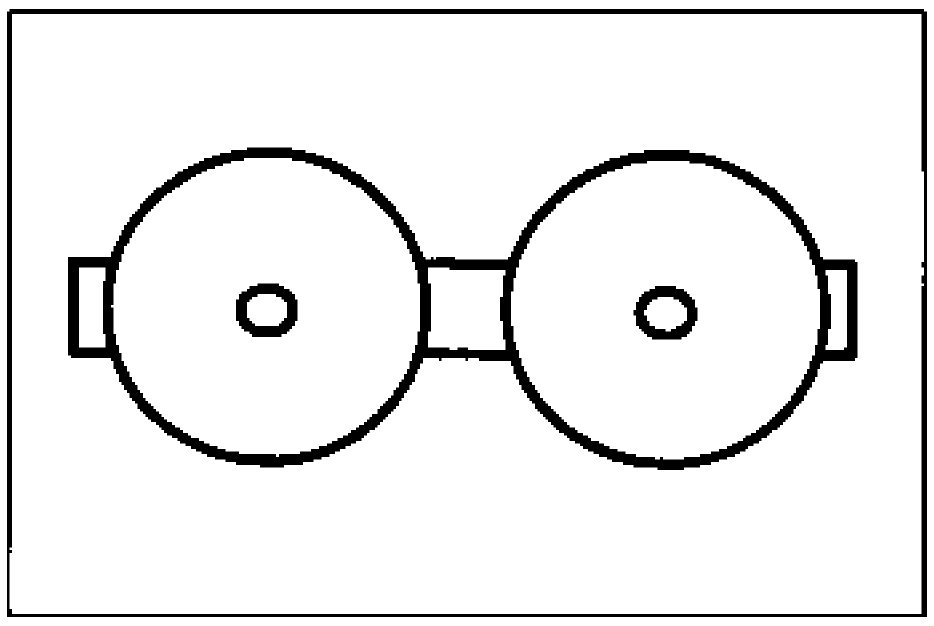
Most of the time was spent creating several simulations to see which was most promising. The tests performed consisted of the dynamic simulations of different vehicle types moving on a craggy surface with a 0.0003 m/s^2 gravity field. All the tests were performed on a motion simulator package called Working Model by Knowledge Revolution. They are further described in the following sections.

5.1.1 Free Hopper

The free hopper design capitalizes on the fact that only a small force is needed to move in a weak gravitational field. It consists of a symmetric four sided body with thrusters at each end. In simulation this vehicle was not promising because of the significant amount of control and realtime feedback needed to accurately maneuver it. In addition a design as such would significantly tax the current available techniques and sensors needed to determine position and orientation with respect to the asteroid surface.



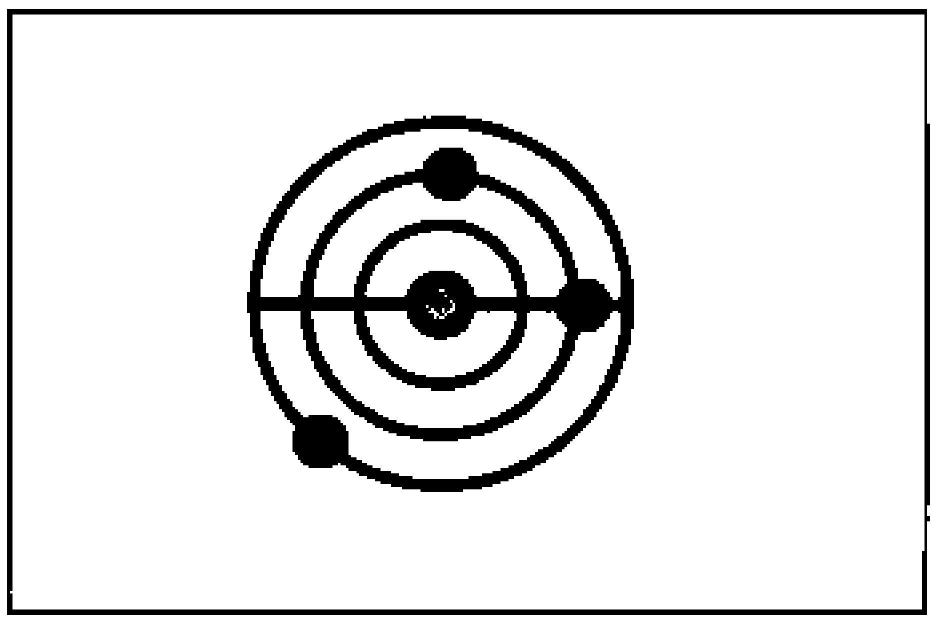
Free Hopper



Wheel Vehicle

5.1.2 Wheeled Vehicle

The wheeled vehicle is so designed to provide a configuration with no up or down due to the realization that any vehicle designed must be capable of tumbling without adverse effects. Accurate values for vehicle mass, gravitational attraction, and surface mechanics were used to obtain realistic results. This design was also found to be of limited use due to the great deal of time it spent floating. During simulations it would touch for a second then fly off again only to touch again some undetermined time later.



Net with Vehicles

5.1.3 Net Vehicle

This simulation consisted of multiple vehicles connected to a net made up of concentric circles. Each circle has a track with a 1 kg vehicle attached providing its own propulsive force. Along the diameter there is a straight track for an additional vehicle. The layout is so designed to minimize the complexity associated with having the vehicles cross tracks. This system produced promising results when simulated and should be further studied.

5.2 Future Simulations

While the previously described simulations have given results for a good start, future simulations will be developed to delve deeper into certain areas.

These future simulations will consist of:

1. Further micro-g traversal studies using Working Model motion simulator
2. Simulate a net of SKITs both in hardware and software
3. C language based distributed, auto re-configurable network algorithm
4. Control of several hardware robots from a distance
5. Autonomous sampling and image acquisition with hardware robots
6. SKIT cooperation experiments for material transport and assembly

The next two sections further describe simulations 2 and 3 listed above.

5.2.1 Net of SKITs

In order to further reveal the strengths and weaknesses of the Net of SKITs concept, simulations will be developed using the three-tiered colony structure. This structure divides the SKITs into three groups: 1) Mobile workers to provide the needed functionality, 2) Mobile helpers to transport tools and supplies, 3) Home Base Unit for storage and communications back to Earth. The net layout will be adapted to a ring of concentric circles to aid in the *Working Model* computer simulation. In this type of layout mobile workers will be able to stay on their specific segment of the net without having to reattach at a cross point as in the rectangle net previously described. After sufficient computer simulation this concept will be tested further in hardware.

5.2.2 Reliable Cooperative Communication Networks

To overcome distances between agents and the home base, cooperative communication relay algorithms will be devised. These algorithms provide the technique for transporting streams of commands and data across long distances using minimal power. The system, when ultimately tested, must be able to initially configure itself for relay of all data back to the home base and to re-configure in the presence of a node becoming inactive. These algorithms will be developed in software simulations then tested in hardware, with SKIT robots as shown in Figure 4.

The following are guidelines to be used to design the *Reliable Cooperative Communication Network* algorithms.

Network requirements include:

- Single frequency broadcast with a signature for each node
- Initial Autonomous Startup with network reconfiguration in lieu of node failure
- Two-way communication from central node to all nodes
- Path for commands from central point to all points or a selected few
- Path for data return from all points in an orderly, reliable manner

Implementation scheme:

- Each node will be independent and run in a semi-random fashion
- Broadcast communication channels will be setup and connected to each node
- Sample commands will be created and sample data streams will be created for nodes
- Control will be commanded from the central node
- Random failures will be introduced and be handled accordingly

Simulation scheme sequence:

- In initial startup, all nodes will listen for commands
- Each node will then wait for an open space to broadcast their signature
- A hierarchy will be setup that prioritizes or orders nodes in a specific manner
- A command will be broadcast from the central point to acquire an image
- After acquisition, data streams will begin to come back
- When all first images are returned reliably, then commands for motion are issued
- When motion is completed, commands for another image acquisition are given, repeat

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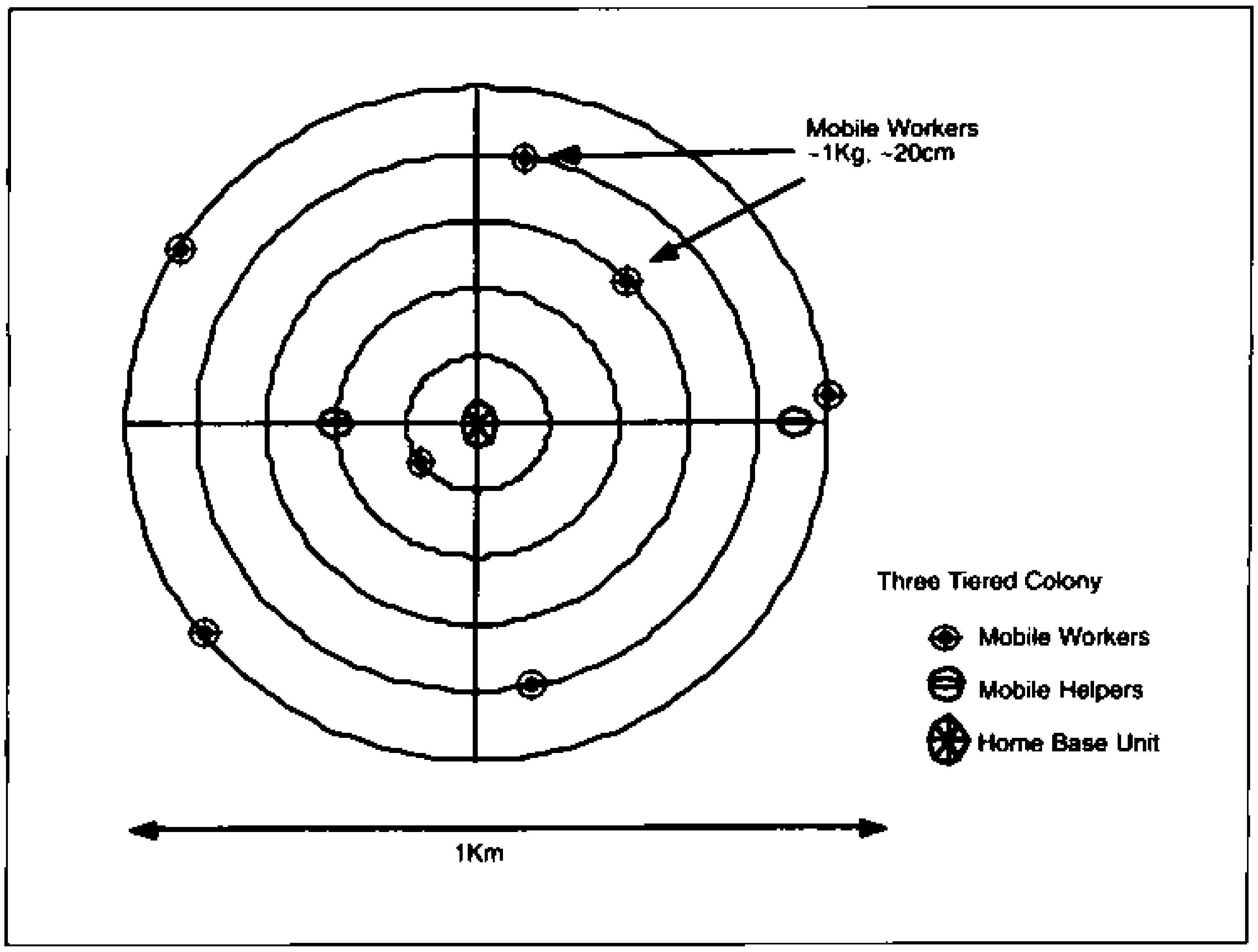

SKIT net simulation with three-tier colony

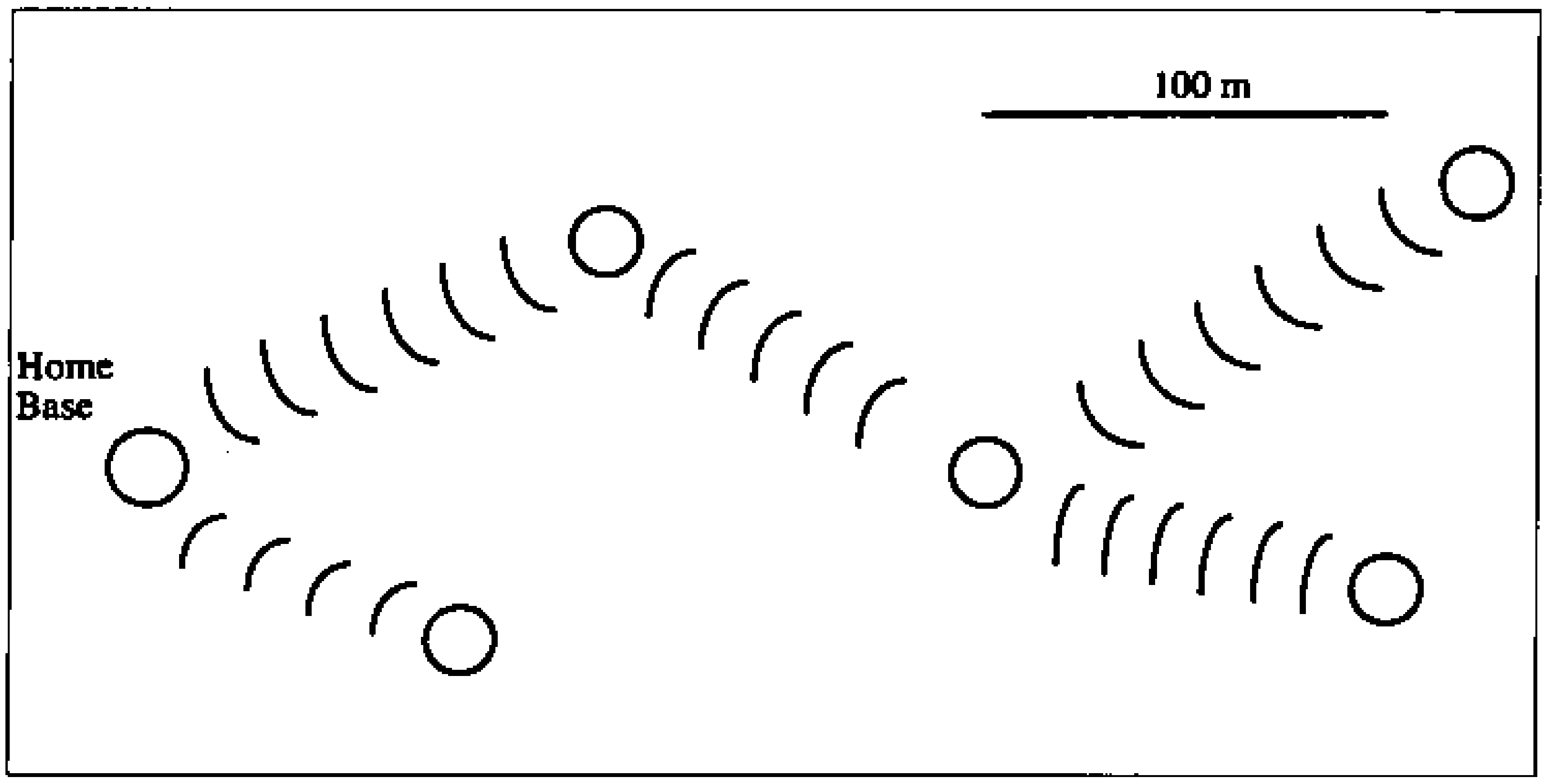

Figure 4 Layout for Tests of the Reliable Cooperative Communication using SKITs

SKIT... (Continued from page 9)

- At random times errors will be introduced and the systems functionality will be tested

Assumptions:

- At least one path is available to all nodes and a critical number of nodes are functioning
- No complete failures in the central node

6. CONCLUSIONS

Every previous occasion on which a first spacecraft reconnaissance mission procured a leap in knowledge of a body, our preconceptions have been found wanting, and major areas of scientific inquiry were initiated. Thus a significant motivation for exploring the asteroids is the potential for many important, unexpected discoveries that we may anticipate when exploring virtually unknown worlds for the first time.

It has become apparent that remote sensing alone will not answer definitively very important questions about the nature of asteroids, their history and relationship to other bodies. This leads us to believe that *in-situ* measurements are needed to establish conclusively what the future uses of asteroids will be. It is by such up-close analysis that the Moon & Mars properties have been established and it should be a good bet that asteroids will likewise provide phenomenal new and intriguing data.

The three parameters of temperature, gravity and rotation rate seem to be the most challenging in designing systems for use on asteroids. In addition, the *uncertainty of asteroid properties*, is also a key driver by having the effect of forcing designers to create systems that must perform in environments where properties are not known within orders of magnitude.

Three different strategies were proposed to overcome the difficulties of low gravity environments while providing a method of performing measurements and work at several distant places on the surface of an asteroid.

Simulations of several vehicles traversing an asteroidal landscape were described with the conclusion that a design with vehicles connected to a net should be further studied. Finally, a plan for this and other types of future hardware and software simulations was provided.

7. ACKNOWLEDGMENTS

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8. REFERENCES

Gehrels, Tom, "Collisions with Comets and Asteroids," *Scientific American*, March 1996, p. 57.

E.M. Shoemaker and E.F. Helin, "Earth-Approaching Asteroids as Targets For Exploration," *Division of Geological and Planetary Sciences*, p. 245.

Binzel, Barucci, & Fulchignoni, "The Origins of the Asteroids," *Scientific American*, October 1991, page 91.

Doody, David, *Basics of Spaceflight Learners' Workbook*, JPL D-9774, p. 14, Dec. 1995.

Chatterjee, Alok, "Missions to the Sun, Planets and Small Bodies," Mission Design Section, Micro Spacecraft for Space Science Workshop, CIT, JPL, July 6 & 7, 1988.

G.K. O'Neill, *Space Manufacturing of Nonterrestrial Materials*, Volume 1, pp. 77-95 (1982). Ed.

Tom Gehrels, *Asteroids*, University of Arizona Press (1979).

Anita M. Flynn, K.R. Udayakumar, David S. Barrett and James D. McLurkin, *Tomorrow's Surgery* (1995).

Kowal, Charles T., *Asteroids: Their Nature and Utilization*, Chichester, England: Ellis Horwood Ltd., 1988.