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

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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 tele-robots could perform the precursor missions.

In light of this, our project was 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 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 and detail some proposed solutions. It presents a tradeoff study performed to develop the SKIT concept and a subsequent simulation and demonstration of the concept.

A unique challenge of this research was to produce substantial results in 1 years' time given the constraint of designing and building devices that are sub-kilogram. Although the requirement of <1 kg 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.

Introduction

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 robotics/AI that would accelerate, or better yet, ignite the colonization of space, first by robots and later by humans.

Our intent was to develop a research program involving actual hardware development to produce prototypes of intelligent miniature tele-robots that could later be improved, space-qualified and used in precursor missions for space resource prospecting, mining and manufacturing. In addition we focused our attention on the effective utilization of the abundant and rich untapped resources of asteroids. Our basic goal in this research was 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 ores an the eventual desire to build structures to support human habitation.

Our plan was 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 tele-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, tele-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 tele-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.

SKIT Tradeoff Study

This section describes the tradeoff study performed to develop a novel SKIT concept. It begins with a description of an example set of relevant mission objectives, then describes the study methodology. Requirements are then listed and tradeoff spaces for alternative designs are described. It ends with a description of a series of mobility simulations performed and is followed by a section on the tradeoff study results.

Mission Objectives

In order to focus our tradeoff study we begin with a short description of a set of plausible mission objectives related to asteroid exploration. This will then give a context in which the tradeoff study can be described. The primary prospecting objectives for asteroids are surface 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 similar tool will be needed.

The following list is an example of the most important properties needed for determining the future use of near earth asteroids.

<u>Bulk properties:</u> Size, shape, volume, mass, gravity field and spin state

<u>Surface properties:</u> Elemental and mineral composition, morphology, texture

<u>Internal properties:</u> Mass-distribution, possible magnetic field

<u>Environment</u> Possible ninteractionear-asteroid gas and dust, solar wind

Payloads useful to determine these properties are:

Essential instruments	Imager (CCD) Gamma or X-ray spectrometer
Highly desirable	I.R. spectrometer Magnetometer
Other instruments	Drilling device Sample collector/ analyzer Mass spectrometer

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

SKIT Tradeoff Study Methodology

With the mission objectives in mind, we began a tradeoff study to produce a novel adequate architecture for a SKIT colony. The purpose of the tradeoff studies was to narrow the number of choices without first analyzing all possible solutions and their interactions. The approach used was based on the Kepner-Tregoe (K-T) decision analysis methodology. The K-T approach uses a set of weighted criteria to compare alternatives by scoring them relative to each other and adding up the weighted scores. In addition a set of overall criteria was developed to guide and simplify the process by using a first level filtering step stated here:

Tradeoff Criteria - 1st level filtering

1. Technology feasibility
2. Simplicity and reliability
3. Minimization of size and weight
4. Mission success probability
5. Concept creativity value

Tradeoff Study Approach

The overall study approach is shown in Figure 2-1 and consists of two components, concept synthesis and concept analysis.

Over the past decades, a considerable effort has gone into the design of robots for

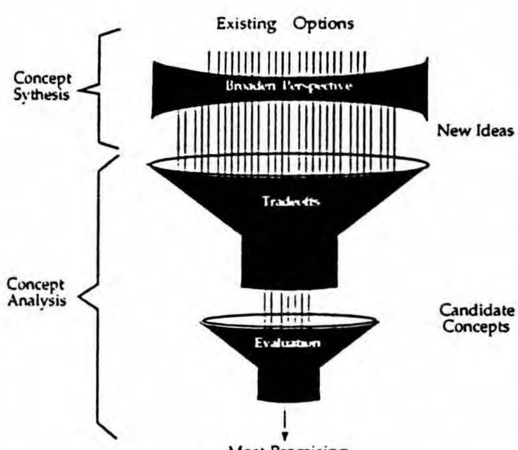


Figure 2-1. Tradeoff Study Process
(Adapted from Spiessbach, A., 1989)

exploration purposes. This database of information is extremely valuable, but not sufficient. Times have changed, and technology advances have made options that were previously rejected now viable. Because of this desire for creative solutions to robotic designs, concept development was not limited to a mere redesign or modification of existing options, but included an effort to broaden the horizon and search out new ideas. With a substantial range of potential solutions provided in the concept synthesis process, design options were then successively filtered out by the concept analysis process. Initially, evaluation consisted of a process of elimination, where qualitative information was sufficient to filter out many options. Quantitative data on performance were then subsequently utilized to further refine the set of options, and separate the promising from plausible ideas. The most promising concepts were further detailed in design and evaluated by simulation. Because of the limitation on knowledge of asteroidal properties, residual uncertainties remained. Consequently, no exact baseline concept was expected to emerge from the current study. Instead, a framework for possible design concepts suitable for the area which we are concerned, primarily surface work on an asteroid, were the final study products.

Tradeoff Study Road Map

The detailed study methodology is shown as an information flow road map in Figure 2-2. System function was defined first, in terms of architectural functional requirements . Structure then followed from function in the form of concrete design alternatives expressed as individual option spaces (i.e. a menu of choice sets is produced for each key design decision). Previously determined design criteria then produced rankings among the choices through a series of tradeoff studies and simulations. The top ranked solutions were then integrated into a candidate overall solution that was then evaluated. Key interfaces between the major activities are shown in the circles. The first step was to define the specific requirements for proposed architectures from the prevailing understanding of mission objectives. Knowledge of the environmental challenges played a major role in applying requirements in the concept generation phase, and the technology state of the art was assessed in parallel with the development of the functional requirements. Previous mission designs, current group robot research and new emerging technology served as aids in generating new alternatives. Literature searches yielded a plethora of current and projected capabilities. Discussions with scientists and engineers at the Jet

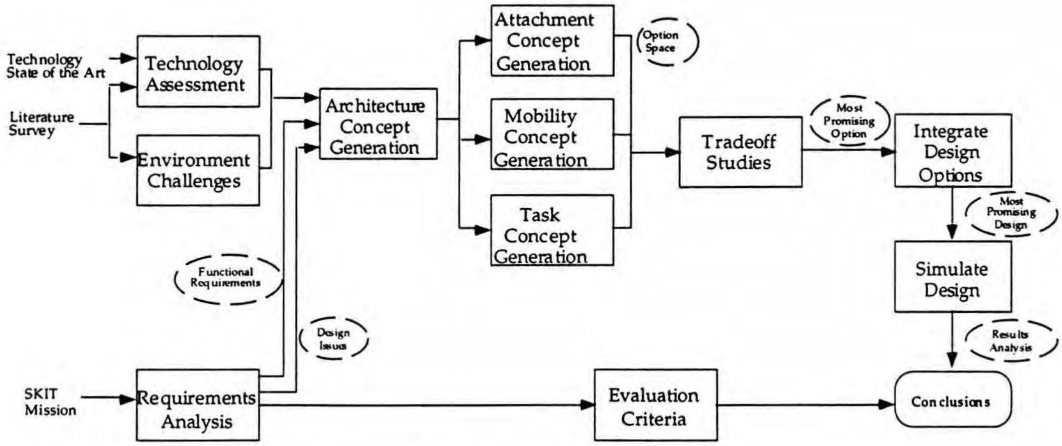


Figure 2-2. Tradeoff Study Road Map
(Adapted from Spiessbach, A., 1989)

Propulsion Laboratory have provided up to the minute information on the content and validity of alternative designs at all levels.

With relative utility and feasibility defined by the requirements and technology assessment, respectively, individual design option spaces for overall architecture, attachment, mobility, and task concepts were generated. The option spaces developed then defined the tradeoff studies that were subsequently conducted.

SKIT Requirements Menu

For the proposed architectures, the issues shown in Figure 2-3 were used to drive the requirements. These issues provided a structure in which adequate requirements could be generated in an environment that was rich in many aspects of importance to the design of multi-robot systems. The following two tables (Table 2-1 and 2-2) describe system objectives for the SKIT architecture. We divided the objectives into two categories musts and wants. The must objectives are mandatory: they must be achieved to guarantee a successful result. When decisions were to be made, an alternative that did not fulfill the must objective would have been left out of the tradeoff study. These objectives were designed to be measurable because they functioned as a screen to eliminate failure-prone alternatives. All other objectives were categorized as wants. The alternatives we generated were then judged on their relative performance against want objectives not on whether or not they could fulfill them.

The function of these objectives was to give us a comparative picture of alternatives, in effect a sense of how the alternatives performed relative to each other.

The data for Table 2-1 was taken from criteria that was considered Mandatory, Measurable, and Realistic. The Must criteria determined the Go/No Go decision for evaluating each alternative. In effect, it was used to determine who plays.

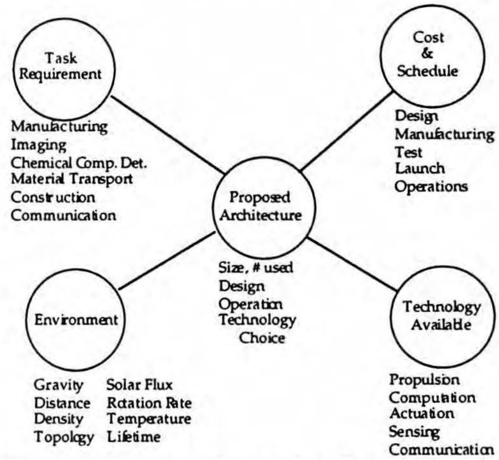


Figure 2-3. Issues that Drive Requirements

The data for Table 2-2 was taken from criteria that was often the best educated guess for each requirement. The *Wants* criteria determined the relative value of each alternative. In effect, it was used to determine who wins.

Tradeoff Spaces

This section lists several of the tradeoff spaces generated during this study for each level of a SKIT

Musts	Requirement Definition	Measured As	Data Source
Operation Life > 12 months	Lifetime of SKIT system on surface of an near earth asteroid	qualitative	Experience
Mass < 1.0 kg	Mass of each SKIT, infrastructure not included but presumed to not be overwhelming	kg	Layout & calculations
Power < 5 watts	Power consumed by each SKIT element (max. continuous)	Watts	Layout & calculation
Speed > 1 cm/sec	SKIT element terrain traversal rates	cm	Calc. /simms
Range > 1000 m	Complete SKIT system must be able to adequately cover an area 1 Km square	meters	Mobility simms
Surface Mobility	SKIT elements must provide stable, controllable mobility	qualitative	Experience
Provide Telecom > 100 BPS	SKIT elements must provide mechanism to send/receive/store data & commands between each other and any relay link needed	bits/sec	Telecom simms
Provide Surface Operations	Provide several distinct methods of performing surface operations, i.e., drilling, chipping, assembly, lifting, moving, heating, etc.	qualitative	Operation simms
Resist Environment	SKIT system must be able to survive challenges of the asteroidal environment (Baseline: Known Properties for Nereus, Nakamura & Abe, 1996)	qualitative	Experience
Enable In-Situ Science	Provide several distinct methods of obtaining desired in-situ science measurements, i.e., imaging, spectroscopy, terrain mechanics, thermal properties, etc.	qualitative	Operation simms
Provide Command and Control	Provide ability for distant operator commands to be received, performed & results returned	qualitative	Operation simms

Table 2-1. SKIT *Must* Requirements Menu

architecture. The tradeoff spaces were categorized in the following ways: SKIT colony architectures, member task organization, mobility options, attachment options, actuation alternatives, and instrument alternatives. In addition to conceiving the tradeoff concepts some effort was spent creating several simulations in an effort to address concerns and gain understanding of mobility issues in a low g environment. These experiments are also included in this section.

SKIT Colony Architectures

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 nor the ability to ignore most reactive motions.

With the above in mind 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 work on the surface of an asteroid. It is followed by a section that details the way task assignments can be broken down for a SKIT system. 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 are presented, then some alternatives are listed and finally pros and cons for each design are given.

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 performs a self health check and waits 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 local 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 re-supply

Initial setup may take substantial time due to distances and terrain difficulties

Possible single point of failure if the mother craft does not operate properly

Network of SKITs

This architecture descrives a group of SKITs separately delivered by cruise spacecraft at 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 communicaiton network, SKITs can begin performing experiments and await further commands to be performed. An additional featyure would be the ability to auto-reconfigure the network in the event of any node failure.

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

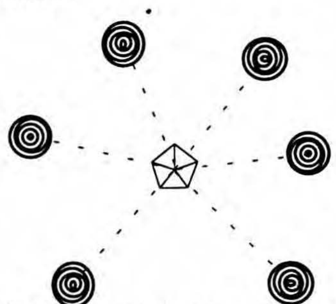
Simple mobility systems due to only short traversals needed around arrival site

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

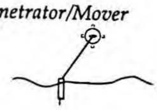
Designs must survive high acceleration impacts

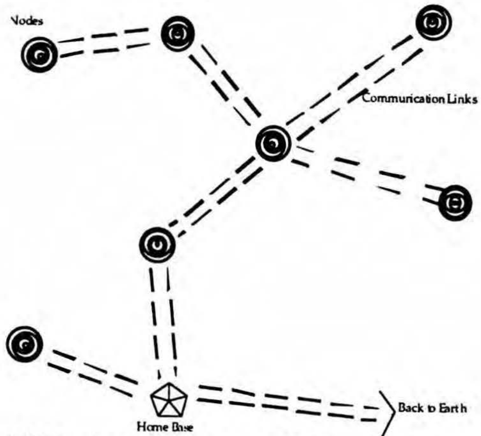
Little is known about the efficacy of penetrators for asteroids



SKITs traverse to/from a central base

Penetrator/Mover





SKITs communicate via a wireless network

Wants	Requirement Definition	Measured As	Data Source
Minimize Mass	Reduce overall system mass	kg	layout & calculations
Maximize Lifetime	Increase overall system lifetime	reliability/ surface cond.	Estimate/ experience
Maximize Traction	Increase system's ability to attach and provide for optimum stability and movement	qualitative	Mobility simms.
Minimize Complexity	Reduce mechanical, electrical, computational, and architectural complexity	qualitative	layout & assumptions
Maximize Recoverability	Increase probability of in-situ diagnosis and repair	qualitative	layout & assumptions
Maximize Range	Increase area covered by the SKIT system	meters	Mobility simms.
Minimize Computation	Reduce complexity that provides computation for tasks	MIPS	calc from simms.
Maximize Operations	Increase both operations and science return	qualitative	Operation simms.
Minimize Cost	Reduce $ amounts to develop and build entire system	relative $	Estimate/ experience

Table 2-2. SKIT *Want* Requirements Menu

Net of Agents

group of SKITs 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, communication, 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.
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 challenges

SKIT net attachment can reduce traversal options compared to unattached designs

SKIT Member Organization

The division of labor scheme applicable to a 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 possible elements at either end is given in the following:

While any point on this graph will have its pros and cons, a third option is to produce a hybrid task breakdown that hopefully is more general and can take from the strengths of each end. One design 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 headquarters control, power management, tool storage, systems status and parts replacement

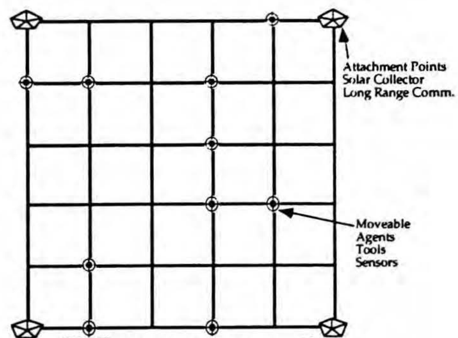
2) *Mobile workers*

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 framework can be used to guide further research into how SKITs will be designed and what each type will be required to perform.



SKITs traverse across a net

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

Heterogeneous ⟷ Homogeneous

Actuation Alternatives

Table 2-3 shows the option space generated for tasks that are beneficial and concern physical actions such as material manipulation and processing.

An effort was made to describe the stage of development and important issues associated. The data was gathered from a survey of past, current and proposed techniques. It is interesting to note that power issues prevail in many of the tasks desired.

Instrument Alternatives

Table 2-4 shows the option space generated for tasks that are desired and concern scientific measurements. An effort was made to describe the operation, status and important issues. The data was gathered from a survey of past, current and proposed techniques. This area is much more developed than the previously described actuation mechanisms area and seems more easily applicable to our efforts at miniaturization.

Task / Principle	Operation/usage	Stage of Development	Mass/size/power issues	Comments
Material Access				
Rappelling	traversal along a tether	Medium	may increase overall mass	structure/power/ comm.
Penetrators	tether attachment	Low	-	dynamics unknown
Burrowing	deep subsurface mobility	Low	Fixed mass indep. of depth	does not rely on platform
Material Preparation				
Rock Fracture	hammer/crusher	High/Low	currently high mass, power	reactive forces effect
Rock sampling	drill/core	High/Medium	-	multiple bit handling
Rock modification	chipping/grinding/ sawing	High/Medium /Low	currently high mass, power	reactive forces effect
Material Processing				
Thermal	heating/melting	Low	currently high mass, power	need energy storage
Joining	welding/casting	Low	currently high mass, power	need energy storage
Material transport				
Manipulation	gripper/scoop	Medium	increased mass	interchangeable tools
Containment	storage containers	Low	increased mass	acquisition sys. tie in
Object Manipulation				
Components	plugging/ unplugging	Low	requires storage facilities	modular parts
Structures	joining/assembly	Low	precision sizing	

Assisted by Dr. Rick Welch, JPL, Pasadena CA, 4/97

Table 2-3. Task Mechanisms for SKITs

Instrument	Science	Operation/usage	Status	Comments
Imager	Geological context, topography, mapping	point and shoot (often build up panoramic & stereo imagery)	Commercial/flight	Basic instrument on every mission
Microscopic Imager	Mineralogical composition	Place/point imager at target of interest often at same point as other instruments	Commercial/flight	JPL developing Active Pixel Sensor based close-up imager
APXS (alpha proton x-ray backscatter spectrometer)	Chemical composition, elemental abundance	placed normal to rock/soil surface or thin layer sample for 1-10 hours	Current JPL Pathfinder/MFEX flight instrument	radioactive hazard (50mCi) expensive ($1M+) not usable in earth atmosphere due to alpha particle absorption
Vis/NIR (0.4-2.5 um) point spectrometer (visible near - infrared)	Mineralogical composition	point at target, may use fiber optics both for light source and to gather reflected light from rock/soil sample	Commercial/flight	Low cost Vis point spectrometers available off the shelf (Ocean Optics)
Vis/NIR (0.4-1.0 um) multi-spectral imager (filter wheel)	Mineralogical composition	Point and shoot	JPL Pathfinder IMP flight camera (stereo)	Soon to be tested on 7/4/97

Surface Attachment

Figure 2-4 gives a pictorial description of the option space considered for surface attachment. Each alternative consists of concept (given in black) and is followed by some issue or example relevant to it. One

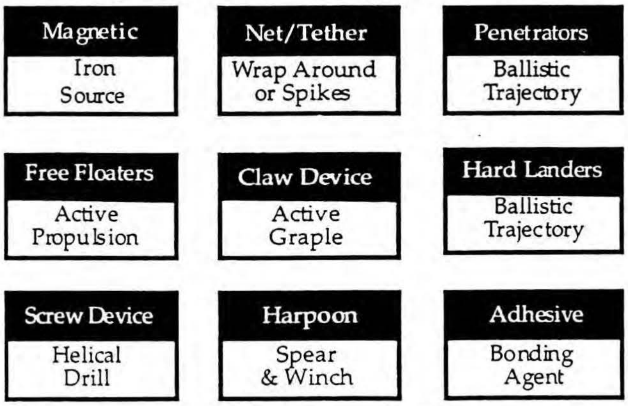


Figure 2-4. Surface Attachment for SKITs

important issue to note is the lack of hard data we currently have about the surface of an asteroid. This causes us to only be able to consider alternatives tentatively until more results of the environment are acquired.

Surface Mobility

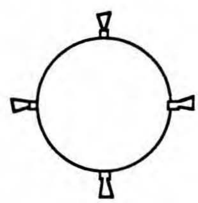
Figure 2-5 gives a pictorial description of the option space considered for surface mobility. It consists of vehicles that roll, walk, rappel, free float, penetrate, and walk along a net or web. One salient feature for the unattached designs was that effort was made to come up with concepts that were symmetrical in several dimensions due to the prediction that vehicles will tend to tumble a great deal during surface traverses.

Mobility Simulations

In addition to developing the tradeoff concepts shown above some effort was spent creating three simulations in an effort to gain some understanding of mobility issues in a low gravity environment. The tests performed consisted of dynamic simulations of different vehicle types moving on a craggy surface with a 0.0003 m/s^2 gravity field. The tests were performed using a motion simulator package called Working Model by Knowledge Revolution. These tests were done in an extremely short time span and should only be used for an initial understanding of mobility issues in a low gravity environment. For this reason, results are described qualitatively.

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 consisted of a symmetric four sided body with thrusters at each end. In simulation this vehicle did not seem too promising for our use due to the significant amount of control and real-time feedback needed to accurately maneuver it. In addition a design as such would significantly tax the current available techniques and sensors needed to determine accurately position and orientation with respect to the asteroid surface.



Free Hopper

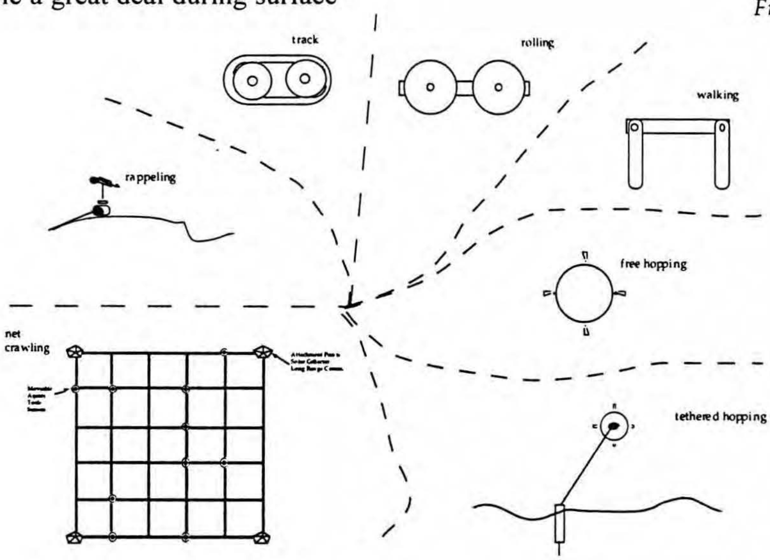
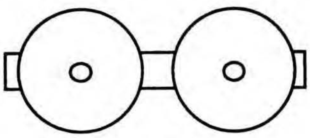


Figure 2-5. Surface Mobility for SKITs

Wheeled Vehicle

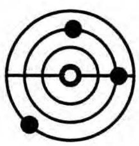
The wheeled vehicle is so designed to provide a configuration with no up or down due to the realization that any vehicle designed must be capable of tumbling without adverse effects. Accurate values for vehicle mass, gravitational attraction, and surface mechanics were used to obtain realistic results.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



Wheel Vehicle

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 that provides its own propulsive force. Along the diameter of the circle 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 in simulation and should be further studied.



Net with Vehicles

Tradeoff Study Results

A trade off was performed on the three concepts produced for the SKIT Colony Architecture option space (Table 2-5). The results from this trade off would then guide the design of the final integrated SKIT concept.

Elements from each of the other option spaces (mobility, attachment, actuation, instrument) were included in these architecture concepts where they seemed most appropriate. The colony architectures were then put through the analysis previously determined to rank their functionality. Values determined following the guidelines set forth were tabulated for each of the components and put into the musts and wants requirements menus. The results from the musts requirements menu show that all three designs received a go decision for each of the requirements stated. This is not surprising since many of these requirements were already in mind when the option spaces were being devised. In addition, the first level filtering probably removed any options that were not appropriate.

The results from the wants criteria were not as clear. It can be said that an ideal alternative perfectly fulfills every condition set for it without adding new difficulties. Unfortunately these alternatives are rare. As can be seen the results were rather similar with two of the designs coming very close. The third design scored less due mainly to its ratings in complexity and traction.

Given the results from the tradeoff study we decided on pursuing the Net of SKIT concept further. The Network of Agents concept was developed further and a concept design was produced. Due to insights acquired from the mobility simulations it was deemed a bit too risky to pursue. The challenge of controlling a free floating vehicle from a distance seemed too complex given current technology. The process described in this section can be further refined and reapplied, when appropriate, at all levels of design. It shows a quick way to generate concepts, compare the alternatives and come up with an adequate solution.

Integrated Design - Net of SKITs

This architecture consists of a number of SKITs attached to a common net as shown in Figure 2-6. The nets overcome the severe difficulty of traversal and attachment in low gravity. They can initially be spun out before arrival or spread out once the SKITs are located on the surface. Their size is to be relatively small compared to the asteroid with several attachment points for each ring. It should be noted that this unfurling and attachment can cause severe challenges to designers. The net in turn could provide a mechanism for: anchoring, mobility, communication, power, etc. The net layout was adapted from the square pattern to a ring of concentric circles. 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. The SKITs can traverse long

Musts		Colony of Agents	Go	No Go	Network of Agents	Go	No Go	Net of Agents	Go	No Go
Life > 12 months			x			x			x	
Mass < 1.0 kg			x			x			x	
Power < 5 watts			x			x			x	
Speed > 1 cm/sec			x			x			x	
Range > 1000 meters			x			x			x	
Surface Mobility			x			x			x	
Telecom > 100 BPS			x			x			x	
Surface Operations			x			x			x	
Resist Environment			x			x			x	
Enable In Situ Science			x			x			x	
Command/Control			x			x			x	
Wants	WT		SC	WT SC		SC	WT SC		SC	WT SC
Minimize Mass	8		6	48		8	64		4	32
Maximize Lifetime	7		6	42		4	28		8	56
Maximize Traction	6		4	24		8	48		6	36
Minimize Complexity	4		4	16		8	32		6	24
Maximize Recoverability	5		5	25		3	15		8	40
Maximize Range	5		5	25		7	35		5	25
Minimize Computation	4		4	16		7	28		6	24
Maximize Operations	7		5	35		3	21		8	56
Minimize Cost	3		4	12		6	18		6	18
Total Weighted Scores:				243			289			311

Table 2-5. Architecture Tradeoff Values

ranges on their ring and also can also converge for tasks requiring more than one. The home base contains tool, instrument and part stores, non-mobile instruments, and sample-return canisters in addition to providing power generation and back to Earth communication.

The three-tiered member organization will be used for task allocation. 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, power generation and communication back to Earth. There will be three types of Mobile Workers:

Mobile Work General (MWG) which has an general purpose actuator to hold samples, mobile tools and mobile instrument

Mobile Worker Device (MWD) which has fixed devices used to manipulate materials such as a drill, core, scraper, etc.

Mobile Worker Instruments (MWI) which has fixed instruments used to measure asteroid properties such as a spectrometer, accelerometer, magnetometer, etc.

The Mobile Helper (MH) will have the tasks:

Material, tool, instrument, part transport (i.e., carry samples, tools, instruments, battery to/from mobile workers)

Collaborative work, i.e. hold sample for MWD (while drilling)

Perform diagnostics on mobile workers

After initial design studies were performed, this concept was further demonstrated in hardware.

Simulated Net of SKITs

In order to reveal the strengths and weaknesses of the Net of SKITs concept a demonstration was 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, and 3) Home Base Unit for storage and communication. The net layout consisted of a ring of concentric circles as shown in Figure 2-7.

In order to provide results in a manageable time a section of the complete net (shown by the dotted line in Figure 2-7) was constructed. This section contained enough elements of the Net of SKITs concept to represent an adequate subset and demonstrate the systems functionality.

Figure 2-8 shows this section magnified and describes what each of the components was in addition to their tasks.

The physical setup is shown in figure 2-9. You will notice the home base unit in the far, bottom left corner. As you move your attention to the right you will see a Mobile Worker Instrument imaging a Mobile Worker General while it is using a tool (scraper) to remove the surface weathering on a rock. Towards the back of the picture is a Mobile Worker Device near the object it will drill for a sample. For scale the dimension of the rectangular surface is four by eight feet. Each robot is a little smaller than an average coffee cup.

The layout of the tether is shown in Figure 2-10. Due to the fact that we were simulating this architecture here on Earth an effort was made to come up with a tether design that was appropriate for a one g gravity environment.

SKIT Tether Concept

It consisted of a long (3 ft) steel wire attached to rollers on the top that slid along the net framework. The bottom was then attached to the SKIT with a swivel. This type of configuration provided the SKIT with an extra normal force downward to simulate one function needed on the real system, mainly to keep the SKITs attached to the surface. The tethers also helped to constrain the range and traversal patterns of the SKITs.

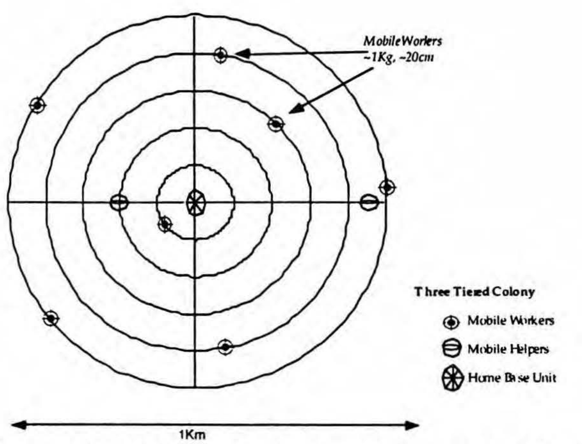


Figure 2-6. SKIT net simulation with three-tier colony

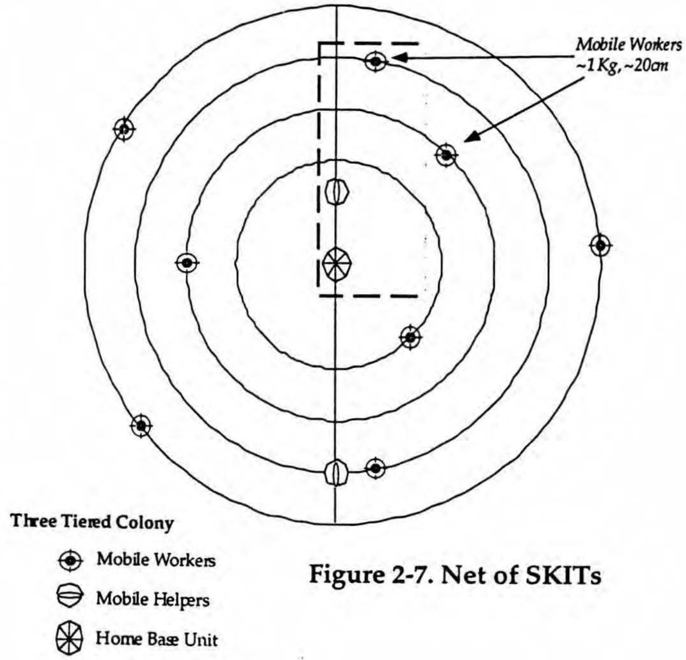


Figure 2-7. Net of SKITs

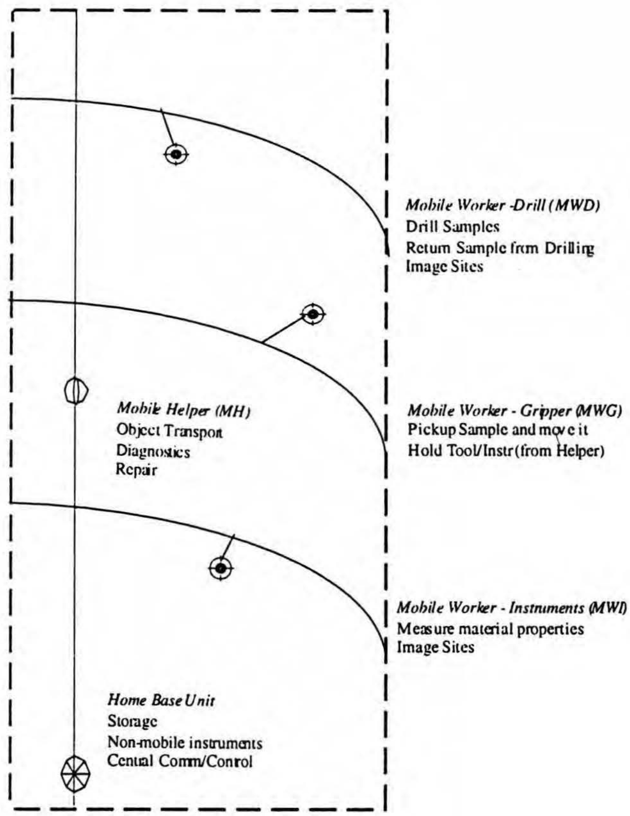


Figure 2-8. Net Simulation Diagram

Three Mobile workers and one Mobile helper were built to demonstrate two types of tasks collaborative work and teleoperated sampling. Collaborative work was important due to realization that more could be done with a group of robots if we capitalize on their ability to cooperate. One example of this consisted of moving parts, samples, tools, instruments, batteries, from the central storage location out to the sites where they are ultimately used and back again. These actions included but were not be limited to: traversing the web, picking up tools, instruments and supplies, handing them from a helper to a worker and ultimately have the tools/instruments/materials put to use by the worker at a work site.

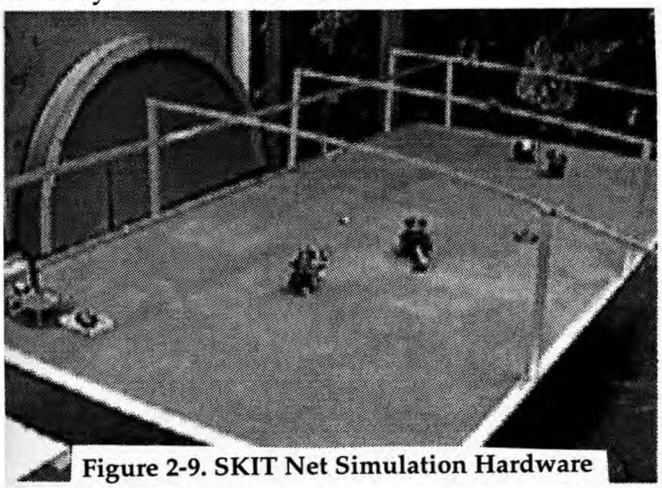


Figure 2-9. SKIT Net Simulation Hardware

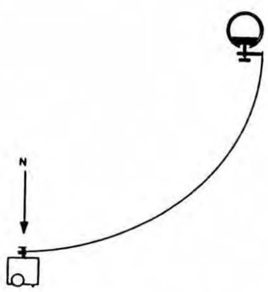


Figure 2-10. SKIT Tether Concept

The second type of task was teleoperated sampling. In order to assess the merit of an asteroid's resources, scientific data about them must be acquired through prospecting. During this demonstration workers gathered samples from the surface and from a drill hole to bring to the helper. In return the helper then carried the samples back to the home base for further analysis and storage. Both these types of tasks were done under remote operator control. To better describe the scenario the participant's task allocations are listed:

SKIT Participants Break Down

Mobile Worker - Gripper (MWG)
- Pickup Sample and move it (Rock)
- Hold Tool to Manipulate Material(Scraper)
- Hold Instrument for measurement (thermometer)

Mobile Worker -Drill (MWD)
- Drill Object
- Return Sample from Drilling

Mobile Worker - Instruments (MWI)
- Measure metallic properties (compass)
- Asteroid structure measurements (accelerometer)
- Measure spectroscopic qualities (filter on camera)

Mobile Helper (MH)
- Material, Tool, Instrument, Part Transport (carry sample, scraper, thermometer, battery to/from MWG)
- Image MWD (while drilling terrain)
- Hold Sample for MWD (while drilling)
- Diagnostics (Check LED's on MWx)

Home Base Unit(HBU)
- Storage (hold tools, batteries and instruments)
- Non-mobile instruments (analyze samples from MWD)
- Sample-return canisters (hold samples from MWG)
- Central Communication (modem base unit)
- Additional possible uses:
  - Gather power (solar cells)
  - Protection (radiation shielding during solar flares)
  - Processing (fast processors for data manipulation)

Attachment Net
- Attachment/Traversal (SKIT will be held down with tethers)
- Localization/Reference (imaged by SKIT to localize)
- Additional possible uses:
  - Power/Comm. Transfer (net carries info./energy)
- Solar Concentrator (focus energy to heat material)
- Earth Comm. (large ring antenna)

This complete setup was demonstrated before a live audience in May 1997. The demonstration took place in Princeton, NJ. at the Space Studies Institute's (SSI) Conference on Space Manufacturing XXIII. SSI is a major sponsor of this development work.

SKIT Agent Hardware

This section details the design of the SKIT agents. Figure 2-11 is a diagram of the Mobile Worker General (MWG) SKIT. It consists of a base unit called a Khepera robot manufactured by K-Team in Lausanne, Switzerland. This base unit has the advantage of being small, modular, easy to control and low cost. From the base unit additional functional modules can be added as needed to create the unit that is desired. An interesting aspect of each module is the presence of a dedicated processor that controls all of its own functions. Above the base is the gripper turret that gives the SKIT object manipulation abilities. This ability makes this agent general purpose since it can carry samples, materials, tool, instruments, etc. Above the gripper turret is the radio turret that every SKIT agent has to communicate over UHF frequencies at ~4800 Kilobits/sec. This unit provides the Home Base Unit the ability to send a message to a specific agent or send broadcast messages to all agents at once.

The top level turret is the Image Processor. Each unit has one of these to gather images from a small photodiode array made by VLSI, in Edinburgh, Scotland. This unit is under development and will be a major product of this research. It is further described in Section 2.7.1.

Figure 2-12 shows what two of these units look like. The left unit is the Mobile Worker Instrument (MWI). This agent is dedicated to gathering scientific measurements with its on-board, fixed instruments.

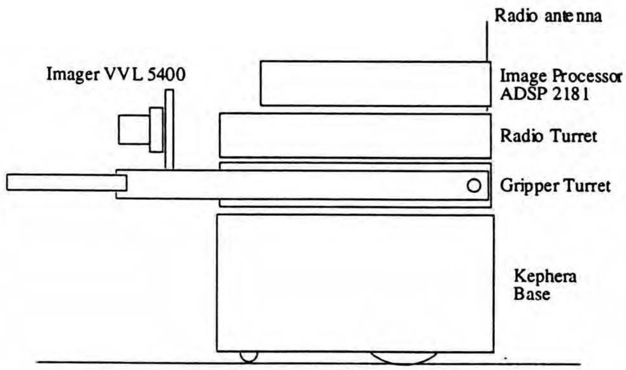
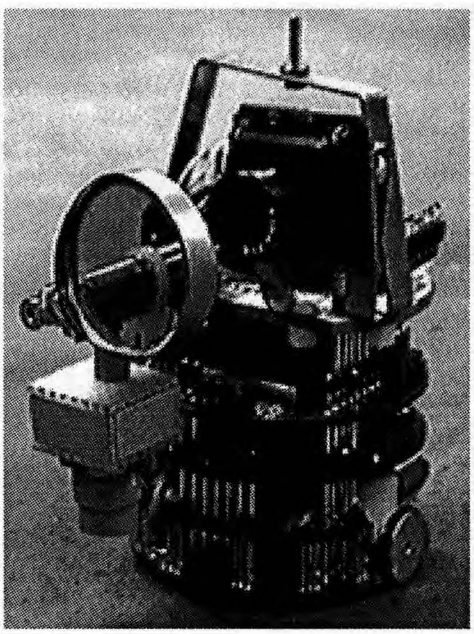


Figure 2-11. SKIT Diagram



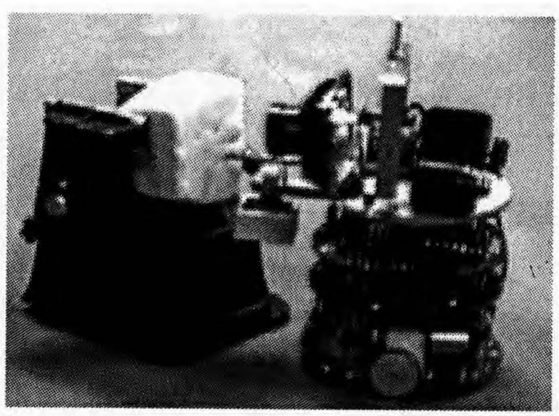


Figure 2-12. Mobile Worker Instrument (left) and Mobile Worker Drill (above).

This current configuration consists of three types of sensors that simulate real instruments, they are:

1) *Color Filter*, this device represents a very common instrument on many spacecrafts, the filter wheel. To operate it an image is taken with it, then it is moved and another image is taken. The difference between the two can give a wealth of information on the surface properties of surrounding rocks.

2) *Magnetometer*, this device consists of an actual compass that gives directional readings when in the presence of magnets. It simulated one of the many instruments available that measure physical properties of the environment.

3) *Accelerometer*, this device is used to measure the physical vibrations of the surface. Although there is little chance of indigenous quakes on an asteroid, one way this instrument can be used is to measure an asteroid's internal structure using ballistic soundings.

Figure 2-13 is an example of a Mobile Helper (MH). This agent is shown working at the Home Base Unit (HBU) picking up a mobile tool(scapper). Next to the scaper is the mobile instrument (thermometer). Behind the thermometer is an example of a battery that can be used to replenish energy to worn out agents. The space under the top surface is used to store samples that have been retrieved.

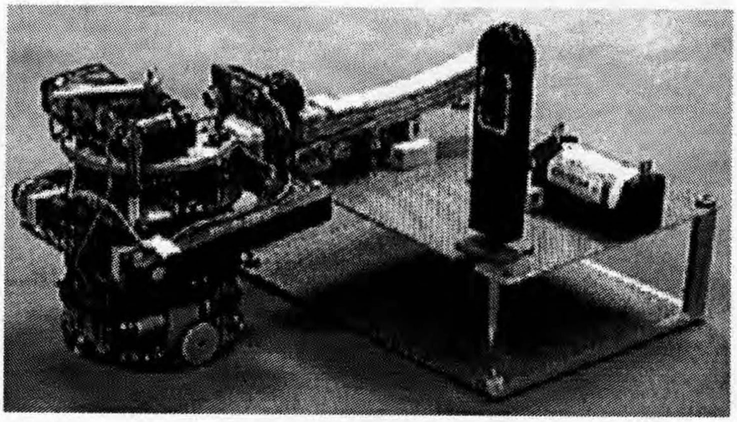


Figure 2-13. Mobile Helper at Base Station

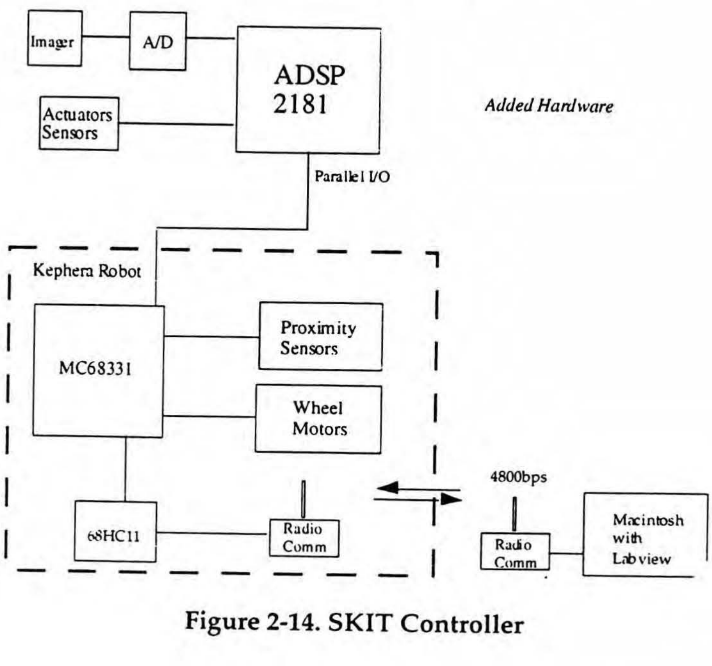


Figure 2-14. SKIT Controller

SKIT Image Processor

Figure 2-14 shows a pictorial representation of the controller on each SKIT agent. The top portion shows the Image Processor section being developed for this research. It consists of a 16 bit Digital Signal Processor (DSP) designed by Analog Devices. This unit is interfaced to a high speed Analog to Digital (A/D) converter through the on-demand Direct Memory Access (DMA) portion of the processor. The A/D in turn is clocked by the photodiode array and samples each pixel as it emerges. Each image processed is first read 8 lines at a time and subsequently compressed using the Discrete Cosine Transform (DCT) algorithm. DCT is the bases of the very popular JPEG compression algorithm that is ubiquitous for storing images.

SKIT Controller

After a complete image is processed, it is sent via a high speed parallel bus to the Motorola 68331 processor located in the Khepera base to later be sent back by radio to the operator's control station. The control station layout for the Mobile Worker Gripper (MWG) is shown in Figure 2-15. The left box is used to display images while the right side contains the controls. The layout was constructed in such fashion

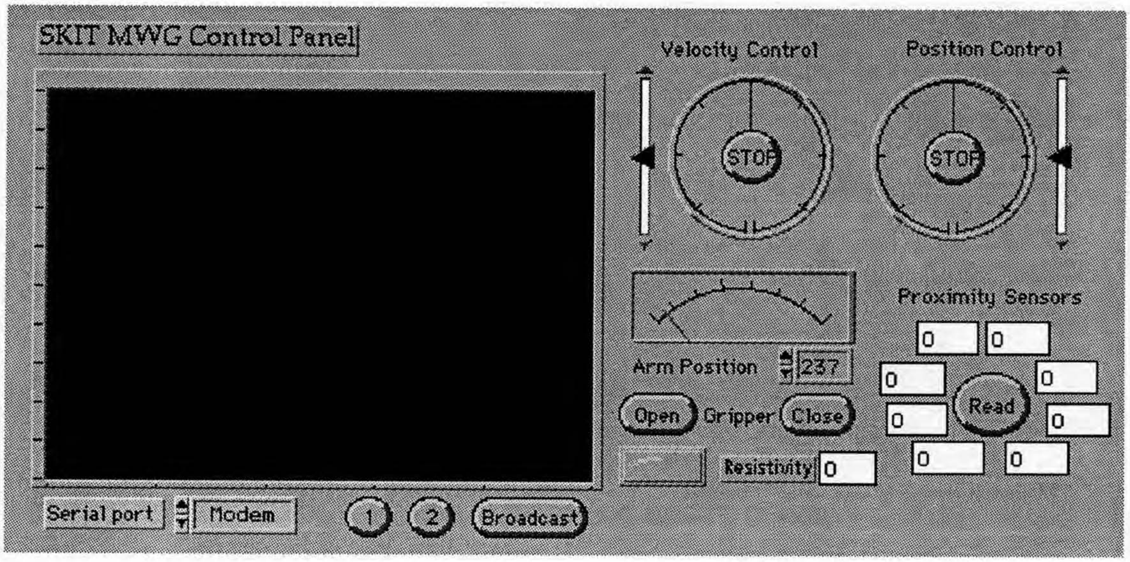


Figure 2-15. SKIT Mission Operations Control Panel

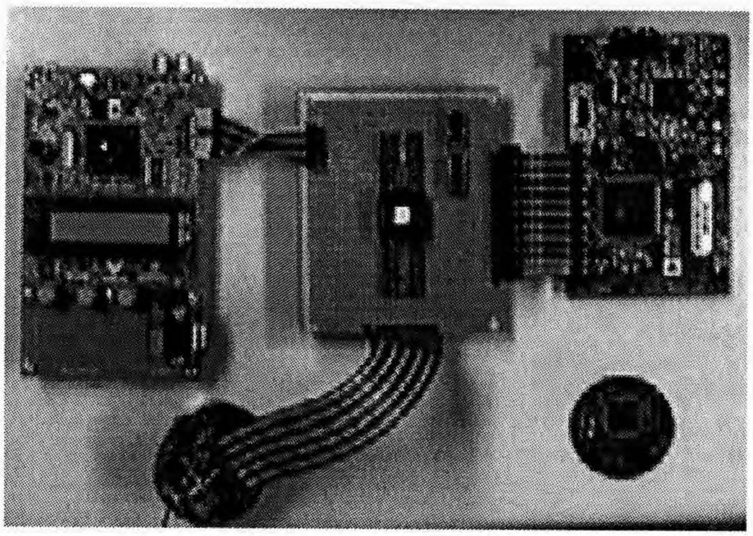


Figure 2-16. SKIT Hardware Breadboard

with the hopes of providing the user with an intuitive sense of how the controls function. Both velocity and position control are provided along with devices to move the gripper and read the several sensors on board the MWG. The image processor is currently running on several breadboards as shown in Figure 2-16. The turret boards have been completely routed and laid out and are awaiting final tests of the bread board functionality before being sent to fabrication. The circle on the bottom right is an example of the size of the final boards after fabrication (about the diameter of a coffee cup).

Figure 2-17 is an image taken with the current bread board set up previously described. The image is a 320x240 pixel array with 8 bit gray scale resolution.

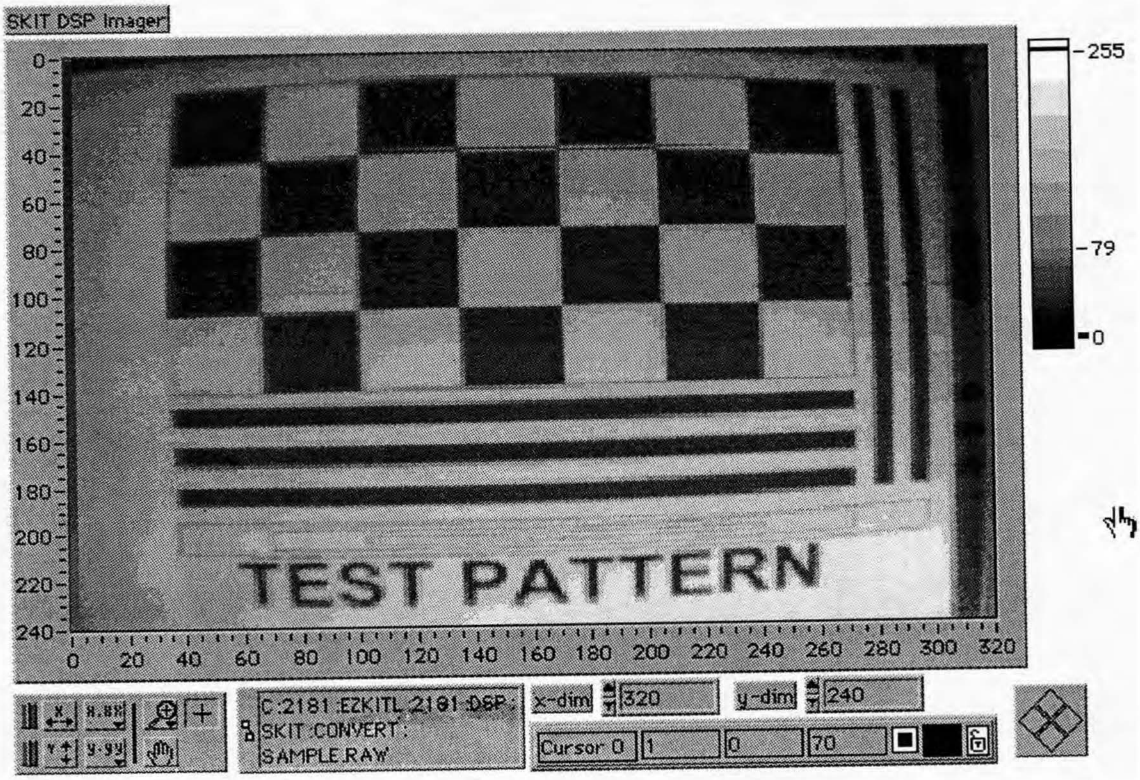


Figure 2-17. Imager Test Picture

Penetrator/Hopper - Abandoned Design

The Hopper/Penetrator device was an attempt to probe the space of ideas in the Network of SKITs concept. Only a preliminary design was completed since the concept was put aside after mobility simulation results deemed un-tethered floating vehicles as less desirable than other designs for our purposes .

Hopper/Penetrator Design

Figure 2-18 shows a pictorial representation of the concept for a penetrator/hopper device.

Each Hopper/Penetrator is separately delivered by a cruise spacecraft at a distance (~10 km) from the asteroid to a desired place on its surface. Upon arrival each device performs a self check and begins network

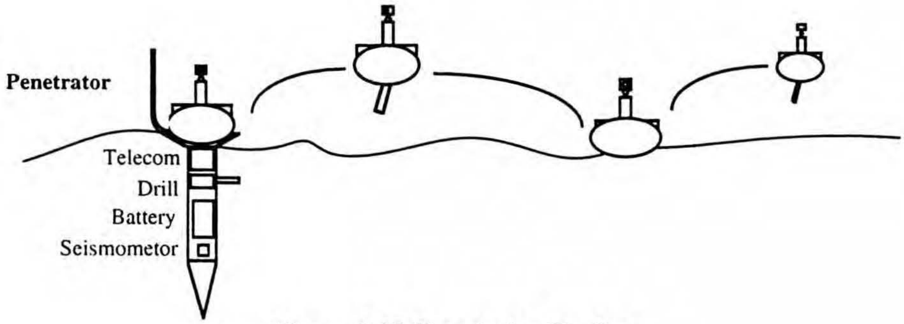


Figure 2-18. Penetrator Design

initialization by determining other units it can reach via wireless radio transmissions.

Overall System Highlights:
- Simple low-mass designs for each function
- Multiple hops due to low gravity & self-righting design
- Drill is designed to overcome low gravity effects and minimize weight

Some of the components are further described in the following sections.

Penetrator Design

Penetrators are designed to relay data from adjacent penetrators destined to the home base. This allows reduced energy requirements by shortening communication range. The penetrators can also sense and record any significant seismic events in their immediate environment.

Penetrator units contain the following:
- a drill used to reach untarnished sample
- a telecom. link to hopper, adjacent penetrator or home base
- an accelerometer to be used as a seismic instrument
- a processor to control drill, imager, communication & data storage.

Hopper Design

Hoppers (Figure 2-19) are designed to take, store and send back images to their respective penetrators. They also have mobility to jump a certain distance in a specified direction.

Highlights of the hopper unit are as follows:
- an imager to view the surrounding surface and take close up views of regolith
- a pan/tilt head to focus the imaging/ spectroscopy device
- a telecom. link for accepting commands and sending science & telemetry data
- a processor to control hopper device, imager, communication and data storage
- an actuator for mobility

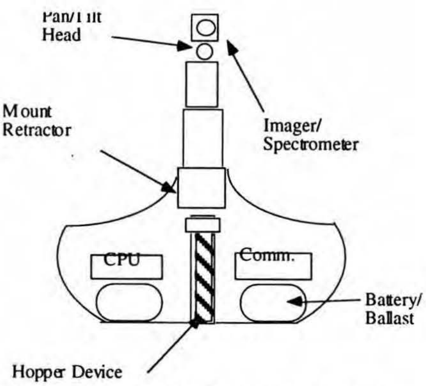


Figure 2-19. Hopper Design

Drill Design

The device shown in Figure 2-20 is used to drill into the surrounding rock around the penetrator, view the sample and send back the image back for post processing on Earth.

The drill contains:
- a drill to bore through the surrounding rock to get to the virgin elements
- an CCD array to send back images for post processing

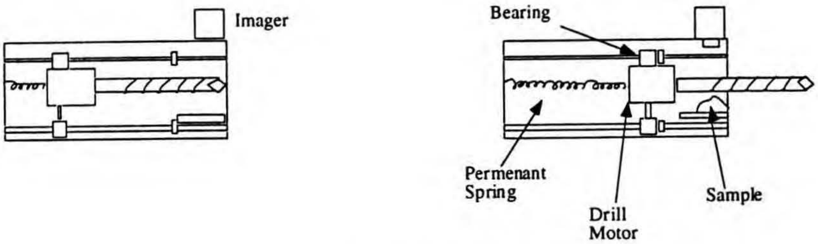


Figure 2-20. Drill Design

Primary Author's Biography

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References

American Institute of Aeronautics and Astronautics, *Space Manufacturing Facilities: Space Colonies*, New York, NY: American Institute of Aeronautics and Astronautics, 1977.

Binzel, Richard, Tom Gehrels & Mildred Shapley Matthews, *Asteroids II*, Tucson, AZ (1989).

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.

Dyson, F., "21st Century Spacecraft," *Scientific American*, Sept. 1995.

Friedman, G. F., "An Expanded Agenda for SSI," *SSI Update,* Jan/Feb. 1995, Space Studies Institute, Princeton, NJ.

Freitas, W., R., Gilbreath, editors, *Advanced Automation for Space Missions*, Proceedings of the 1980 NASA/ASEE Summer Study held at the Univ. of Santa Clara, Santa Clara, CA June-August 1980.

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

Grey, Jerry , *Space Manufacturing Facilities (Space Colonies)*, Princeton/AIAA/NASA Conference (1975).

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

Lewis, John S., *Space Resources: Breaking the Bonds of Earth*, New York, NY: Columbia University Press, 1987.

Maryniak, Greg, "Self-Replicating Machines for Space," Space Studies Institute Publication, Princeton, NJ.

Miller, Dave, *Small Robots, Big Missions*, 1992.

O'Neil, Gerard, *The High Frontier: Human Colonies in Space*, Princeton, NJ: Space Studies Institute Press, 1989.

O'Neil, Gerard, *Space Manufacturing of Nonterrestrial Materials*, Volume 1, pp. 77-95 (1982).