A Novel Information Management Architecture for Maintaining Long-Duration Space Crews

Phase I Advanced Aeronautical/Space Concept Studies Final Report

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Submitted:
January 7, 2002

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A Novel Information Management Approach for Maintaining Space Crews in Long Duration Space Flight

NIAC Phase I report

Abstract

The current approach to spaceflight countermeasure development is evolutionary and involves improving measurement technology and validating countermeasure protocols. Ultimately, however, this approach is limited by the inability to create a controlled scientific environment on the spacecraft to evaluate physiologic effects accurately. A revolutionary approach to countermeasures involves placing the crewmember in a monitored environment, where data are collected and analyzed continuously and automatically. In this instance, the lack of scientific control would be balanced by the ability to detect important trends rapidly and give the crew useful feedback on their status. Implementing such an information collection and management system in the extreme conditions imposed by long duration space flight for exploration class missions, (bandwidth and power limitations, limited communication with ground control, demands on crew time, etc,) requires a novel approach. We present an architecture for monitoring people during spaceflight using an expert agent-based system. This architecture incorporates the known benefits of expert agent-based architectures (efficient bandwidth use, load balancing), but would advance the technology into a new, more demanding application—monitoring human physiology. This Phase I project examined the basic architecture, sensors and tradeoffs that would be needed for a proposed implementation of this architecture. The problem of bone and calcium loss in space was chosen as the test case.

The study showed that an agent-based architecture design is feasible to collect and analyze data on calcium loss. The major limitation is that although considerable physiologic research has been done in the area, few studies exist that are directly applicable to the design of a bone loss monitoring system. Those that do exist suggest that physical activity, acid-base balance, diet and the effects of pharmacologic countermeasures will be the most important factors to monitor. Although several useful sensors exist now, and improved sensors are likely for the future, sensors that directly measure some key parameters of interest (for example, impact loading on the hip) are likely to be too invasive to be acceptable. New approaches to automated sensor data analysis and interpretation offer the potential to extract useful data from the sensors.

The major conclusions of the Phase I study are:

1. Agent-based architectures have been demonstrated for engineering and other applications, but have not been applied to the kinds of noisy data that would be generated in a biomedical application. Existing implementations of agent-based monitoring systems, such as the D'Agent application and ActComm project described in the text, could be modified to meet this needs of an bone loss /kidney stone prevention algorithm.

2. Many studies have been done on calcium metabolism and the factors that affect urinary calcium in the setting of spaceflight are known or can be predicted. Despite this,

however, the kinds of mathematical relationships that would be need to be defined between urinary calcium and activity, acid-base balance, etc. do not exist due to a lack of specific data.

3. Numerous sensors exist now or are likely to be available in the future that can measure a whole variety of relevant parameters in the urine. The main sensor challenge to developing this system is developing relationships between activity sensors and skeletal loading. These relationships do not exist and are not likely to exist in the future.

For the future, we propose a series of test studies to determine if an agent-based system could accurately provide information on bone loss countermeasures from the data likely to be acquired from identified sensors.

I. Problem Statement

Long-duration spaceflight produces a variety of undesirable physiologic changes (bone loss, muscle atrophy). To prevent these problems, countermeasure programs are under development. The physiologic research needed to develop countermeasures is difficult due to the multiple sources of variability in human physiological measurements and the physiologic differences that exist between subjects. For example, although spaceflight is known to produce significant bone loss on average, some crewmembers have returned with no measurable loss and others have had losses much greater than average (20) . This kind of variability is atypical for most engineering systems, where the input/output relationships are more fully defined.

The approach to developing countermeasures involves ground-based studies, where multiple variables can be controlled and the countermeasure can be developed by minimizing other interfering factors. One example of this is a controlled metabolic study where diet, exercise, temperature etc. are all rigorously controlled. Samples of urine, blood and feces are taken frequently and processed in a laboratory. These studies are very productive and provide excellent guidance for countermeasure development. This level of scientific control would be unacceptable, however, for a long space voyage because it is intrusive and time consuming.

The result of the countermeasure development efforts is a countermeasure plan, which is used uniformly in all crew and usually not optimized for each individual. At present, the crewmembers have little insight during the mission into whether the countermeasure program is being successful in their case. The opportunities to evaluate the effectiveness of the countermeasure program come after the flight, when it is too late to intervene productively. This approach to countermeasures (a standardized plan with post flight evaluation) is being used for the International Space Station, and proposed for Mars journeys.

A more desirable approach to countermeasures is to be able to monitor the relevant changes continuously and to feedback to be crewmembers when action needs to be taken.

To do this, however, the system has to be able to extract relevant physiological information out of a vast amount of noisy data. The kinds of controls that would be available in detailed countermeasure evaluation studies would not be present and instead the system would have to be able to account for the variability that exists. The goal of this Phase I effort was to describe an architecture that could be used in the future to maintain humans in space for long durations using unobtrusive monitoring with software mobile agents as the information management and analysis mechanism.

II. Technical Approach

A. Introduction

Providing ongoing monitoring and feedback for optimizing countermeasures requires a suitable architecture. Agent-based systems provide an excellent base for developing a system that could deal with physiologic data. In this type of architecture, mobile agents (small analysis and detection programs that can travel across a computer network under their own control), take responsibility for various portions of the countermeasure evaluation task. The agents can collect and analyze data, send alerts and communicate with a central analysis system. This approach works well for monitoring well-characterized systems, such as an information retrieval and analysis system for military target identification. This approach has not been applied to systems as complex as physiological systems that are adapting to a novel environment like spaceflight. The use of such an architecture would free the crew from data collection and analysis tasks and alert them only as necessary when action needs to be taken. The two main advantages of this approach are that:

a. the crewmember would not need to collect and analyze samples. Instead of trying to run tightly controlled studies, the agents would track for trends over time to pull the relevant long-term data out of the day-to-day information.
b. it would promote autonomy so that the crew would have all the information needed to maintain themselves, without resorting to data evaluation on the ground. Currently, the crew has to wait until after the mission to find out how effective the countermeasure program was. With an agent-based system the crew would get automated, relevant feedback.

In addition, this approach represents a fundamental difference in the approach to countermeasures. Currently, considerable effort is spent to reduce the variability in physiologic measurements by development of more specific measures and by running tightly controlled countermeasure evaluation studies. These approaches are evolutionary, in that they are trying to improve upon the existing countermeasure development paradigm. The agent-based approach to monitoring is **revolutionary**, because:

a. Rather than try to measure a few variables very precisely, this approach uses continuous monitoring combined with adaptive software algorithms to evaluate key trends in the data,

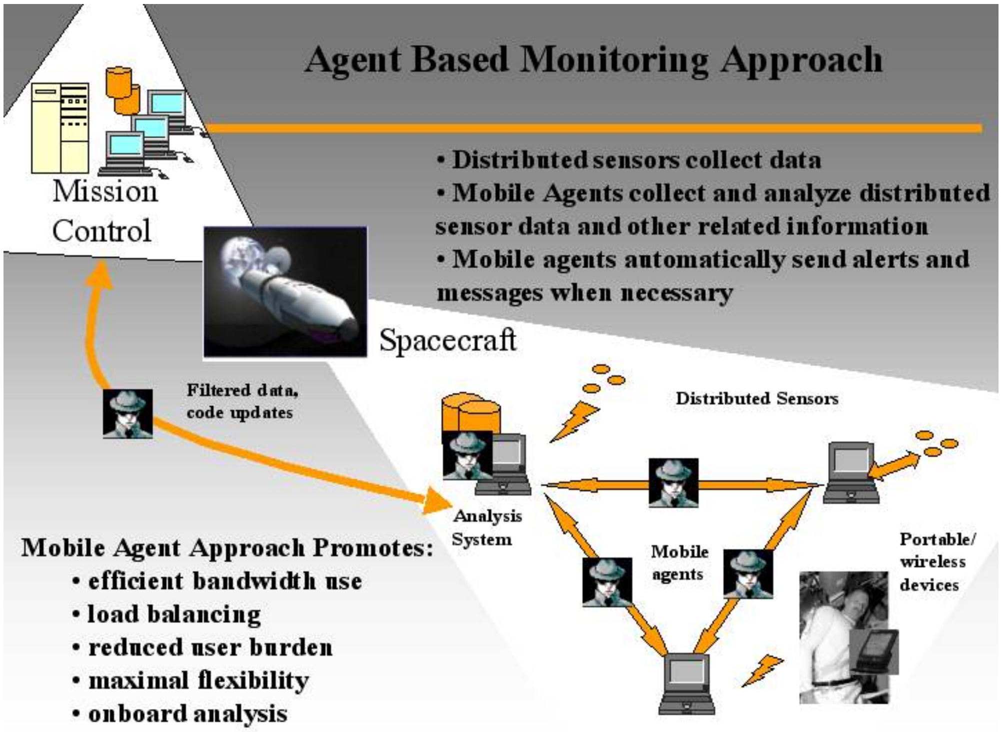
b. Instead of data collection sessions with tight controls, this approach would measure and account for major sources of variability, and include them as parameters measured by the agent-based system.

To evaluate this approach to maintaining humans in space, we selected a test case—bone loss and kidney stone prevention during spaceflight—and examined the factors that would be needed to produce a successful agent-based architecture for maintaining bone mass and preventing kidney stones in space. To guide this study we selected a parameter that would be used as a marker for bone loss and kidney stone propensity in space (urinary calcium excretion), and then examined existing data on the relationship of this factor to a variety of factors that could produce bone loss. In addition, we examined the sensors that are available (or would be available in the future) for monitoring factors related to bone loss (impulse activity, urinary parameters, etc.). An agent-based architecture was proposed that could incorporate data from the various sensors and produce a viable countermeasure evaluation system. The trade-offs and future studies needed to build a prototype system were identified.

B. Agent-Based Architecture Overview

Agent software technology has recently become a highly publicized and active research area. Generally speaking, software agents are autonomous software programs that can adapt to an operating environment and an application's needs. Being autonomous, many software agent behaviors and programming issues are related to Artificial Intelligence and the two fields of research have significant areas of overlapping interest and technology. Mobile agents are agents that can migrate from computer to computer under their own control at times of their own choosing. Mobile agents provide an efficient means of gathering and monitoring information in heterogeneous, distributed, low bandwidth networks. Computers on the International Space Station are linked on a network and such an architecture seems likely for a Mars spacecraft as well.

Figure 1 shows a proposed agent-based architecture for human physiological monitoring. Distributed sensors throughout the spacecraft collect data important for determining physiological status. The agents will do any required processing on the data, and will generate alerts and messages in case of sensor malfunction or clearly anomalous data. The analysis system on the spacecraft interprets the data from the agents, and can communicate with ground control.



Agent Based Monitoring Approach

- Distributed sensors collect data
- Mobile Agents collect and analyze distributed sensor data and other related information
- Mobile agents automatically send alerts and messages when necessary

Mobile Agent Approach Promotes:

- efficient bandwidth use
- load balancing
- reduced user burden
- maximal flexibility
- onboard analysis

Figure 1. Schematic of an agent-based monitoring approach. Agents monitor a variety of parameters and provide the information to an analysis

Allowing agents to move within a network offers several major advantages to a complex, distributed computing environment. By moving from node to node, agents can more effectively balance load when some computing nodes become overloaded, communications bandwidth requirements can be reduced by moving a computation to the data in case the data is large, persistent queries on a remote database become more efficient if the querying is done locally at the database server as opposed to over a network and overall the overall computing environment is more flexible because mobile agents allow new functionalities to be introduced dynamically into a computing system. The flexibility of offered by the mobile agent system will also make it easier to create individualized countermeasure programs.

An architecture based on mobile agents can benefit long-duration space flights for several reasons. New functionalities can be implemented dynamically from earth-based mission control; on-board resources will be more effectively and efficiently utilized (such as on-board communications bandwidth, processor and memory capacities of different on-board computing platforms, and earth-to-craft communications resources). In defense applications, mobile agent systems have been successfully demonstrated in areas such as target identification (11), logistics (3), and small unit operations (12).

C. Background on Bone loss in Space

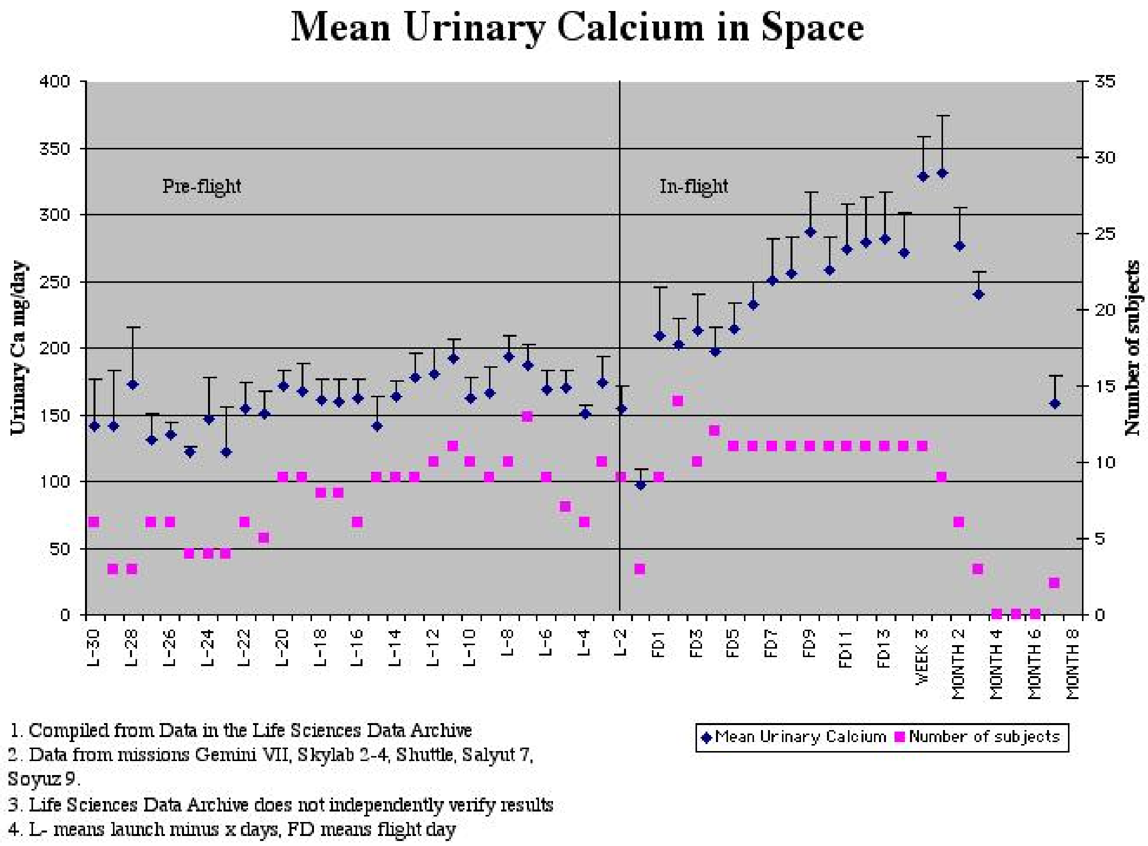
Low light levels, high ambient CO_2 concentrations and minimal skeletal loading -- all known consequences of long duration space flight -- can have a profound effect on the skeleton. Within a few days of entering weightlessness, urinary calcium excretion increases by 60-70%. Data from the Skylab program in the early 70's showed that approximately 0.3% of total body calcium is lost per month while in space (22) (21). This loss, however, is not distributed equally throughout the skeleton. Data compiled from the Mir program show that the hip may lose greater than 1.5 % of bone mass per month (7;9). The upper extremities show minimal or no bone loss and bone mass in the skull may actually increase. All the data to date collected in space have been done in the setting of an active exercise countermeasure program.

Although bone is lost at a rapid rate, recovery is slower. Recent data from the Mir program in one individual showed that while 12% of bone was lost during four and one half months in space, recovery of 6 percent took one year (10). Follow up of the Skylab crewmembers five years after their one to three month flights suggested that not all the bone lost on the mission had been recovered (19). In patients who recover completely or partially after spinal cord injury (where bone is lost in a similar way to space flight), bone is still not recovered completely 1 year after recovery (23).The quality of the recovered bone in these instances is not known.

These data indicate that bone loss is a significant problem for long duration space missions and one that must be adequately monitored and controlled. Also, the data suggest that it is much more effective to prevent bone loss, rather than try to recover lost bone after a mission. The current approach to monitoring bone loss, however, is to measure the loss after the flight and then attempt to correlate this with the crewmembers activity and adherence to the countermeasure program during the flight. What is needed, however, is the ability to monitor the bone loss as it is occurring so that the crewmember can take action.

A significant change in bone density must occur before it can be detected using current techniques. To measure minute changes in bone density would require major technological advances that do not appear likely. What is needed instead, is an early warning of bone loss so that action can be taken as early as possible. Figure 2 shows a graph of calcium that appears in the urine when crewmembers are in space. This calcium comes from several sources, but bone is the key source of this increase in urinary calcium. If this urinary calcium level could be monitored and correlated with the variables that are known to affect bone (lack of activity, high CO_2 levels, diet), the potential exists prevent bone loss, by intervening early and providing meaningful feedback on what is happening to the skeleton in space.

The increase in urinary calcium also has another effect. The increased level of calcium in the urine also increases the risk of kidney stone formation, and kidney stones have been a problem in long-duration spaceflight. So, controlling the level of urinary calcium could help prevent kidney stones, in addition to preventing bone loss.



1. Compiled from Data in the Life Sciences Data Archive
2. Data from missions Gemini VII, Skylab 2-4, Shuttle, Salyut 7, Soyuz 9.
3. Life Sciences Data Archive does not independently verify results
4. L- means launch minus x days, FD means flight day

Figure 2. This graph compiles existing data on urinary calcium excretion in space. Urinary calcium rises promptly upon entering weightlessness and tends to stay elevated. The blue diamonds show the urinary calcium values and the pink squares show the number of individuals who had data at that time period.

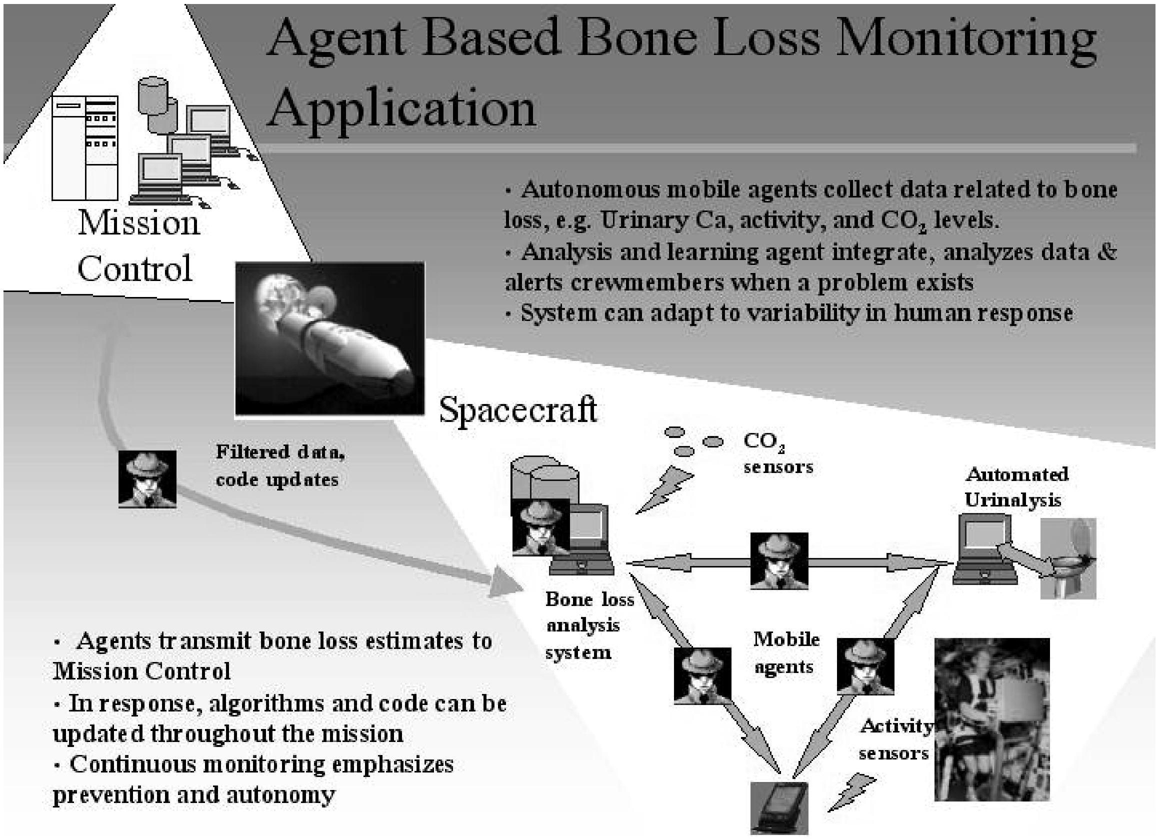
III. Results

In the following sections we present analyses performed to determine the feasibility of building a revolutionary countermeasure program based on a mobile agent architecture. We discuss the system components required to gather, analyze and store information required for the system, examine the relationship between calcium loss and various parameters that can be measured, present a survey of measurement devices that could potentially be utilized in the bone loss monitoring application, and describe the details of the design approach for the analysis software needed to process measurement data, estimate bone loss and recommend therapy for crewmembers.

A. Agent-Based Bone Loss Prevention Architecture

Overview

The nature of the bone loss problem in space suggests the architecture outlined in Figure 3. The system would consist of sensors to estimate and track bone loss, software to perform various collection and processing tasks, and computing hardware to interface with sensors, run the software components and store information. In this automated approach, mobile agents are used as the information management mechanism. Automated devices integrated into the network, either through wireless or wired connections, would be interrogated by mobile agents to provide information specific to the application.



Agent Based Bone Loss Monitoring Application

- Autonomous mobile agents collect data related to bone loss, e.g. Urinary Ca, activity, and CO_2 levels.
- Analysis and learning agent integrate, analyzes data & alerts crewmembers when a problem exists
- System can adapt to variability in human response

- Agents transmit bone loss estimates to Mission Control
- In response, algorithms and code can be updated throughout the mission
- Continuous monitoring emphasizes prevention and autonomy

Figure 3. Agent based architecture for monitoring bone loss. Sensors collect information, which is then processed by mobile agents and analysis software. Agents deliver alerts and pertinent information to crewmembers and also communicate with mission control.

The information management system at the core of the bone loss monitoring system must be capable of performing many functions, including:

- Automatically collect results of urinalysis from an automated urine collection system
- Continuously monitor crewmember activity through sensors placed on crewmembers and on exercise equipment
- Collect data on the diet the crewmember is ingesting.
- Persistently monitor CO_2 levels within the spacecraft by interfacing with sensors throughout the spacecraft
- Transport the urine analysis, physical activity, and $CO_{2\ \mathrm{results}}$ to a bone loss analysis agent
- A bone loss analysis agent would analyze data, spawn new mobile agents to collect additional information as needed (such as medical history), and alert crewmembers when their countermeasure program requires alteration.
- Transmit and receive relevant information, including code updates, to ground stations as necessary

Although the individual tasks are complex, these requirements fall into several basic categories of functionality: information retrieval (from sensors and databases, both persistently and as scheduled events), information analysis (to determine bone loss and recommend therapies), and information push (code updates, messages to crew and mission control).

Mobile Agent Application Development

Implementation of the mobile agent architecture requires a software development platform, preferably one specifically designed to produce mobile code applications. The D'Agents system is a Dartmouth-developed mobile-agent system whose agents can be written in Tcl, Java, and Scheme. D'Agents has extensive navigation services (16), security mechanisms (6) and debugging and tracking tools (8). Like all mobile-agent systems, the main component of D'Agents is a server that runs on each machine in a network. When an agent wants to migrate to a new machine, it calls a single function, *agent_jump*, which automatically captures the complete state of the agent and sends this state information to the server on the destination machine. The destination server starts up an appropriate execution environment (e.g., a Tcl interpreter for an agent written in Tcl), loads the state information into this execution environment, and restarts the agent from the exact point at which it left off. Now the agent is on the destination machine and can interact with that machine's resources without any further network communication. In addition to reducing migration to a single instruction, D'Agents has a simple, layered architecture that supports multiple languages and transport mechanisms. Adding a new language or transport mechanism is straightforward: the interpreter for the new language must support two state-capture routines, and the “driver” for the new transport mechanism must support asynchronous I/O and a specific interface.

Figure 4 shows the D'Agents architecture. The core system, which appears on the left, has five levels. The lowest level is an interface to each available transport mechanism. The next level is the server that runs on each machine. This server has several tasks. It keeps track of the agents running on its machine, provides the low-level, inter-agent communication facilities (message passing and binary streams), receives and authenticates agents that are arriving from another host, and restarts an authenticated agent in an appropriate execution environment. The third level is a shared C/C++ library that is used for all supported languages and provides an interface to the agent servers. The fourth level of the architecture consists of the execution environments, one for each supported agent language. All of the languages are interpreted, so the “execution environments” are just interpreters, namely a Tcl interpreter, a Scheme interpreter, and the Java virtual machine. For each incoming agent, the server starts up the appropriate interpreter in which to execute the agent. It is important to note that most of the interface between the interpreters and the servers is implemented in the C/C++ library and shared among all the interpreters. The language-specific portion is simply a set of stubs that call into this library.

The last level of the architecture embodies the agents themselves, which execute in the interpreters and use the facilities provided by the server to migrate from machine to machine and to communicate with other agents. Agents include both moving agents, which visit different machines to access needed resources, as well as stationary agents, which stay on a single machine and provide a specific service to either the user or other agents. From the system's point of view, there is no difference between these two kinds of agents, except that a stationary agent typically has authority to access more system resources. The agent servers provide low-level functionality. Dedicated service agents provide all other services at the agent level. Such services include navigation, high-level communication protocols, and resource management.

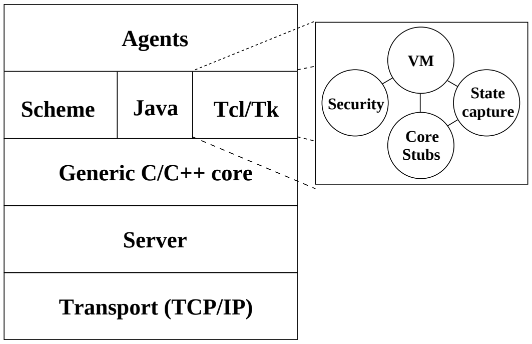
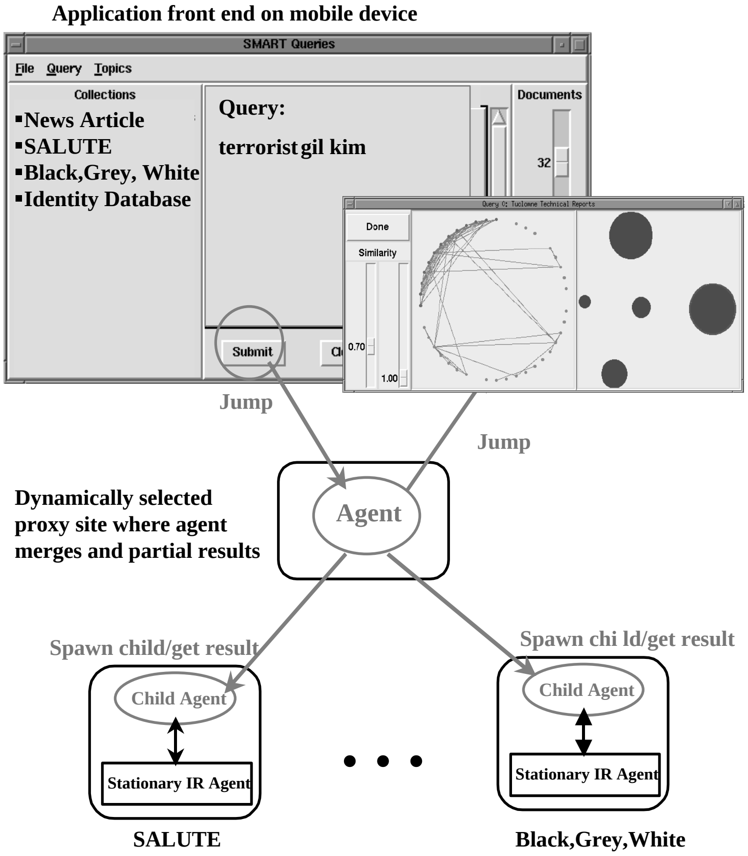


Figure 4. The architecture of the D'Agents system. The core system has five levels: transport mechanisms, a server that runs on each machine, an interface library, an interpreter for each supported agent language, and the agents themselves. Support agents (not shown) provide navigation, communication and resource management services to other agents.

A typical information query application constructed using D’Agents is shown in Figure 5. The application's task is to search a distributed collection of data sources for information relevant to a user's query. The user enters a free-text query into a front-end GUI. The GUI then spawns an agent to actually perform the query. This agent makes two decisions. First, if the connection between the home machine (i.e., the user's machine) and the network is reliable and has high bandwidth, the agent stays on the home machine and executes the query remotely. If the connection is unreliable or has low bandwidth, which is often the case if the home machine is a mobile device, the agent jumps to a proxy site within the network. This initial jump reduces the use of the poor-quality link to just the transmission of the agent and the transmission of the final result, conserving bandwidth and allowing the agent to proceed with its task even if the link goes down. The proxy site is dynamically selected according to the current location of the home machine and the document collections. Once the agent has migrated to a proxy site, if desired, it must interact with the stationary agents that serve as an interface to the data source collections. If these stationary agents provide high-level operations, the agent simply makes RPC-style calls across the network (using the inter-agent communication mechanisms). If the stationary agents provide only low-level operations, the agent sends out child agents that travel to the document collections and perform the query there, avoiding the transfer of large amounts of intermediate data. Information about the available search operations is obtained from the same directory service that provides the location of the document collections. Once the agent has the results from each document collection, it merges and filters those results, returns to the home machine, and hands off the results to the front-end GUI for display to the user.

For the bone loss and kidney stone prevention system, a similar use of agents could be implemented. In such a system, the databases would contain baseline and medical information about individual crewmembers. The agents would also connect to sensor systems designed to capture other relevant information. One major difference would be the query interface. In the bone loss and kidney stone prevention system, the collection of information would occur automatically, without a specific input query being entered by the users. However, there would be interfaces for maintenance and informational purposes. Figure 6 shows how the information retrieval application in Figure 5 would be adapted for the bone loss and kidney stone prevention application.



Query:
terrorist gil kim

Figure 5. An information-retrieval application in which D'Agents is used. The user enters a free-text query via a front-end GUI; the GUI then launches an agent that will search a distributed collection data sources for information relevant to the query. The agent first jumps to a proxy site if the link between the user's machine and the network is unreliable or has low bandwidth. Then, if the query requires multiple operations against each search engine, the agent launches child agents that travel to the search-engine locations and perform the query steps locally to the engine. If the query requires only a single operation, the agent will interact with the search engines remotely.

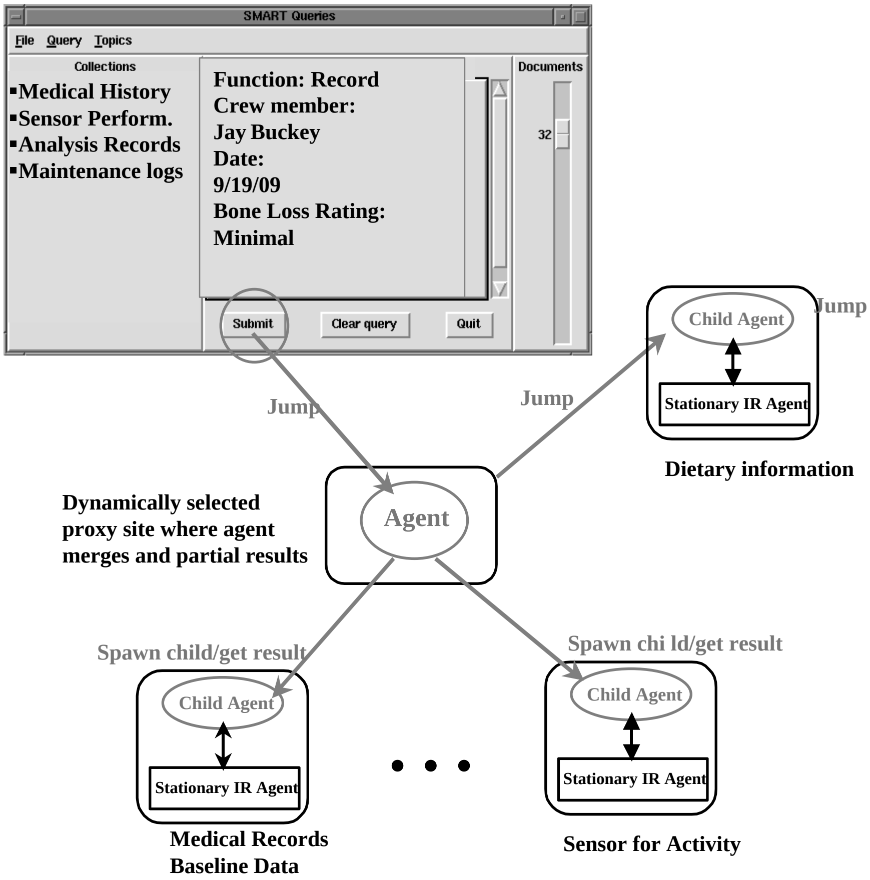

Function: Record
Crew member:
Jay Buckey
Date:
9/19/09
Bone Loss Rating:
Minimal

Figure 6. The bone loss and kidney stone prevention system shown in the context of the D’Agents information retrieval application.

Agent Based Systems as A Framework for Information Management

There are a number of design issues to be considered in the development of agent-based architectures. These issues include processing and analysis speed, physical power, scalability, and software maintenance. Since implementation of an agent based architecture to monitor bone loss was beyond the scope of this study, we determined the feasibility of our general approach by comparing the specific design issues for this application with agent systems that have already been implemented. Here we describe a military application of mobile agents, called the ActComm (Active Communications) project, which was implemented using D’Agents. After describing the ActComm application, we then draw conclusions about the suitability of the agent-based approach for bone loss prevention based on similarity of the system requirements to the ActComm application.

The ActComm scenario involves an urban warfare mission in which a terrorist group is trying to gain control over the civilian population in an emerging democratic nation. The scenario plays out a situation in which friendly forces are looking for suspected terrorists who may be coming to a meeting at a building that is a known location of insurgent activity. An intelligence team at headquarters has intercepted one or more phone calls and determined that a terrorist faction is planning to meet in the building.

Battalion (BN) headquarters dispatches a platoon of soldiers, who take up observation posts (probably hidden) around the building and report all activity to headquarters. If the known terrorists come to the building, the soldiers will secure the building and capture the terrorists.
Each soldier carries a portable computer equipped with a global positioning system (GPS) unit to determine the soldier's position and a wireless Ethernet card to communicate with other soldiers. All the soldiers have an electronic map of the urban area where the building is located.

The current positions of the other soldiers are displayed on the map. The soldiers enter into their computer descriptions of the people that they observe entering the building. Each observation is sent to headquarters so that mission analysts can determine whether any of the persons who are observed is one of the suspected terrorists. To help make their determination, analysts can send pictures to the soldiers, and ask them to identify whether the person they have just seen is in one of the pictures.

Both the soldiers in the field and those at headquarters can query military databases that live in the main network. The testbed has three available databases: (1) news articles arriving on a military news feed; (2) transcripts of intercepted phone calls; and (3) descriptions of people relevant to the mission at hand and the operational area. The database containing the descriptions is called a black-gray-white (BGW) database, since each person is marked as bad, neutral or good. The soldiers in the field primarily search the BGW database, while the team at headquarters searches all three databases.

Back at the headquarters, the analysts monitor the situation in the field and make complex queries to determine whether the suspected terrorists are in the vicinity of the building. The analysts have established a mobile agent with a persistent query to monitor the three available databases for relevant information. For example, in the scenario, a persistent query to report transcripts of any phone calls involving one of the suspected terrorists has been launched, and the analysts receive notifications of such phone calls. After a short period of time, during which both text and pictorial information has passed between headquarters and the platoon, the analysts at BN headquarters determine that two insurgent leaders are already in the building, and the soldiers in the field confirm that the person they saw just enter the building was also a known terrorist. At this point, BN headquarters orders the platoon to secure the building and capture its occupants.
Shortly after the platoon has captured the building, BN headquarters is ordered to relocate to prepare for another anticipated mission. With the wireless computers that are being used at headquarters, it is only necessary make the move to the new location and check the application display. Any information transmitted to headquarters while the computers were down arrives as soon as the computers are set up again.

To summarize, mobile agents are used for three purposes in the test bed scenario. First, an active-messaging system is implemented on top of the mobile-agent system. Each message is wrapped inside a mobile agent, which carries the message through the network. The mobile agent approach to messaging promotes message delivery in spite of network discontinuities and low bandwidth connections.

A second application of mobile agents in the ActComm scenario is that mobile agents that move from the soldiers' machines into the main network perform all multi-step queries. The agents interact with the needed databases without using the unreliable, low-bandwidth link that connects the soldiers to the main network. The agents complete the queries faster, and do not waste bandwidth by sending intermediate results back to the soldiers.

Finally, after a soldier sends an observation to headquarters, headquarters might send back a set of pictures. The soldier confirms whether the person she saw is in one of the pictures. In the testbed, headquarters sends not only the pictures, but also the *code* that displays the pictures and allows the soldier to browse them. The code and pictures are sent as a single mobile agent. The picture-browsing code could have been installed on the soldier's machine before the mission begins. The mobile agent, however, eliminates the need for the pre-installation step, something that is important if the mission is planned rapidly, and the soldier has never been involved in a "picture" mission before.

The ActComm application successfully demonstrated that mobile agents can be used as an information management architecture to provide near-real time information retrieval and analysis, alerting, and code maintenance functions. These characteristics map directly to the categories of functionality listed in the previous section for the bone loss prevention requirements: information retrieval (from sensors and databases, both persistently and as scheduled events), information analysis (to determine bone loss and recommend therapies), and information push (code updates, messages to crew and mission control). Thus, the results of part of the Phase I study determined that:

1. A bone loss prevention system for long duration space flight would require various hardware and software components for monitoring, analyzing, and storing data over the course of the long duration space flight

2. The environment onboard a spacecraft designed for long duration space flight would have limited bandwidth, and power, and space restrictions

3. Applications such as the ActComm project demonstrate that agent based frameworks can operate successfully in this type of extreme environment

A discussion of specific agent functionality for the bone loss prevention application is best understood in light of the relationship between calcium loss and various parameters, which must be measured to calculate the bone loss. Therefore, we leave the discussion of specific agent functionality and analysis software for Section D and proceed with the discussion of urinary calcium relationships.

B. Urinary Calcium Relationships.

Urinary Calcium as a Marker for Bone Loss

To design a bone loss prevention architecture there must be some measure of bone loss that will be tracked to indicate whether the countermeasure program is successful. One approach is to measure the density of bone at particular locations. Dual-frequency X-ray absorptiometry is the most commonly used method to measure bone mass and is what is used clinically to follow patients with bone loss. Although this technique can detect changes as small as 1%, on a space mission it could take a month or more to develop this degree of bone loss. During that time the crewmember may be participating in an ineffective countermeasure program, but would not have any insight into this. If a change in the program is made, it would take another month or two to determine if the change was effective. A more rapidly responding marker of bone loss would be more useful.

Many markers exist

When bone is broken down and lost, markers of this loss appear in the urine. For example, N-telopeptide is a breakdown product of collagen and the levels of N-telopeptide in the urine will rise when bone is being lost (17). A portable kit that can be used at home is now available to make measurements of N-telopeptide (http://www.ostex.com/Products/Point_Of_Care_Description.asp). At present, however, this kit is costly, and would make a validation study very expensive. Also, while this marker is specific for bone, it does not give information needed for kidney stone prevention, which is also important in long duration spaceflight. In the future, however, this parameter could easily be added to a bone loss prevention architecture. To validate a system now, however, a marker that is inexpensive to assay would be preferable.

Urinary calcium most influenced by other factors but easy to measure.

The levels of urinary calcium rise dramatically upon entering weightlessness, as figure 2 shows. Similarly, when drugs are given that reduce bone loss, the amount of calcium that appears in the urine drops markedly (15). This shows that urinary calcium is a rapidly responding marker of changes in bone metabolism. Also, it is easy and inexpensive to measure.

When urinary calcium is used as a marker of bone breakdown, however, it is usually done in metabolically controlled settings. In these settings the dietary composition is controlled to provide a known amount of calcium in the diet and all the calcium that is lost (both urinary and fecal) is monitored. In this way, fluctuations in urinary calcium that might result from changes in dietary intake or differences in absorption can be accounted for. Such a level of dietary control and monitoring is difficult to achieve.

Such a level of dietary control was achieved in the Skylab program and demonstrates how urinary calcium measurements have been used in the space program. Figure 2 shows the dramatic changes that occur in urinary calcium excretion in space. Most of the data in that graph are from the Skylab program and they show that the increase in urinary calcium is not subtle and is long lasting. When examined in more detail the data may also reveal how urinary calcium measurements could be used to determine the effectiveness of countermeasure programs.

The Skylab program had three visiting crews, Skylabs 2, 3, and 4. After Skylab 2, when the crews were felt to have lost excessive bone and muscle mass, the exercise countermeasure program was increased dramatically. On the later missions, and particularly on the longer Skylab 4 mission, crews performed more exercise than had been performed by the crew of Skylab 2. Post flight assessments of the Skylab 4 crew were that this increase in exercise had been effective. If this had been the case, and if urinary calcium could be used to monitor bone loss, it would be expected that the pattern in the urinary calcium levels would differ between the early and the late Skylab crews.

To determine assess this we plotted the 24 hour urinary calcium from the Skylab 2 mission on the same scale as the urinary calcium data from the same period of flight for the Skylab 4 mission. The results of this effort appear in Figure 7. These data should be interpreted with caution since the two groups of crewmembers differed in their baseline excretion of calcium and cannot be directly compared. Nevertheless, the data do suggest that the difference in countermeasure programs may well have been reflected in the urinary calcium excretion and raise the possibility that regular monitoring of urinary calcium excretion could provide insight into the effectiveness of countermeasures.

In clinical medicine recent evidence suggests that urinary calcium measurements may be useful even without tightly controlled dietary monitoring. In kidney stone prevention programs, the amount of calcium in the urine over 24 hours is used to determine the effectiveness of kidney stone preventive measures (2). These analyses are done repeatedly over time without dietary control and still show the effects of treatment. The fact that 24-hour urine collections can be used clinically over time, even without dietary control, suggests that an effectively designed bone loss prevention architecture could be used.

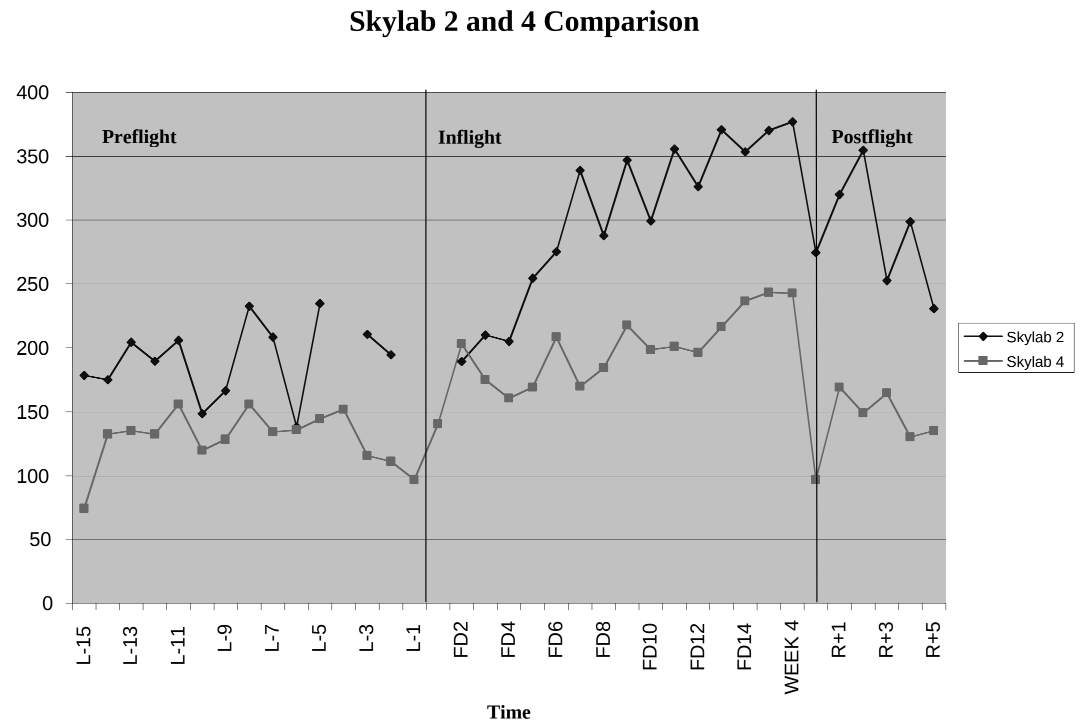


Figure 7. Comparison of urinary calcium excretion for the first month of flight for the crews of the Skylab 2 (28 days) and Skylab 4 (84 days) flights. The Skylab 4 crew (bottom tracing) followed a more aggressive countermeasure program, which may have been reflected in a more modest increase in their urinary calcium excretion. The data on urinary calcium excretion were not available to the crew during the mission.

In summary, urinary calcium was chosen as the marker to follow for the bone loss prevention architecture because:

1. it changes rapidly in response to bone unloading.
2. it is easy to measure
3. evidence from Skylab suggests that it may be useful for monitoring countermeasures.
4. clinical data suggest that it can be used over time for monitoring, even without dietary controls.
5. it is relatively inexpensive
6. changes in urinary calcium also provide information useful for preventing kidney stones.

Urinary Calcium Relationships

To design a system based on urinary calcium, the basic relationships that exist between urinary calcium and the factors that might change urinary calcium need to be described.

To help organize the phase I effort we developed a urinary calcium loss function that includes the various factors that might influence urinary calcium during spaceflight. This function is shown in Figure 8. The equation is based on existing knowledge of calcium metabolism and physiology. The equation includes some factors that are interrelated (such as dietary protein and acid-base balance, or impulse activity and overall activity), but this was done to insure completeness. Although each factor in the equation is known to affect urinary calcium excretion, the exact relationship (i.e. relative magnitude, time course) may not be well described.

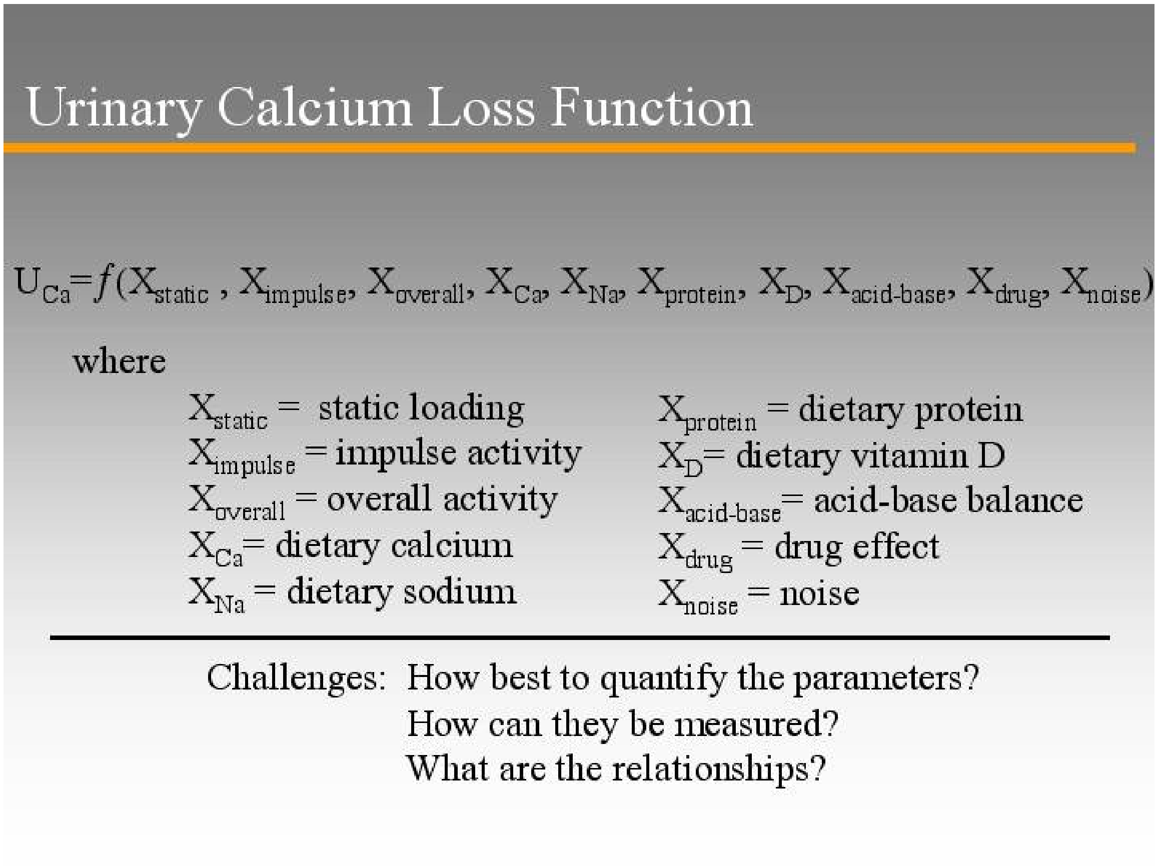
One objective of the Phase I effort was to perform a systematic literature search for published studies that might have information that could be used to describe the relationship for each factor in the equation. For each major factor in the equation the general relationship to urinary calcium was described (i.e. a direct or inverse relationship) and then information was sought to see if the time relationship could be determined (i.e. immediate (within days), delayed (within weeks), exponential, logarithmic, linear etc.). The results of this effort are shown in Appendix A, which includes a spreadsheet with all the supporting information for the urinary calcium relationship. The net result was that very few studies existed where urinary calcium was collected frequently enough to determine the time course of the change. The effect of anti-resorptive drugs was the most studied area, but even in this area data on the time course of the effect on urinary calcium was not directly determined.

The results of this area of the Phase I effort determined that:

1. Although calcium metabolism has been well studied, very few studies have measured urinary calcium frequently enough to provide the information needed for a mathematical model.

2. Based on the literature and planning countermeasures for spaceflight, the areas where relationships are most important are for drug effect (e.g. bisphosphonates), activity and acid-base balance.

3. To design a bone loss architecture, studies to establish urinary calcium relationships for key parameters will be needed.



Urinary Calcium Loss Function

$$U_{Ca} = f(X_{static}, X_{impulse}, X_{overall}, X_{Ca}, X_{Na}, X_{protein}, X_D, X_{acid\text{-}base}, X_{drug}, X_{noise})$$

where

X_{static} = static loading
$X_{impulse}$ = impulse activity
$X_{overall}$ = overall activity
X_{Ca} = dietary calcium
X_{Na} = dietary sodium
$X_{protein}$ = dietary protein
X_D = dietary vitamin D
$X_{acid\text{-}base}$ = acid-base balance
X_{drug} = drug effect
X_{noise} = noise

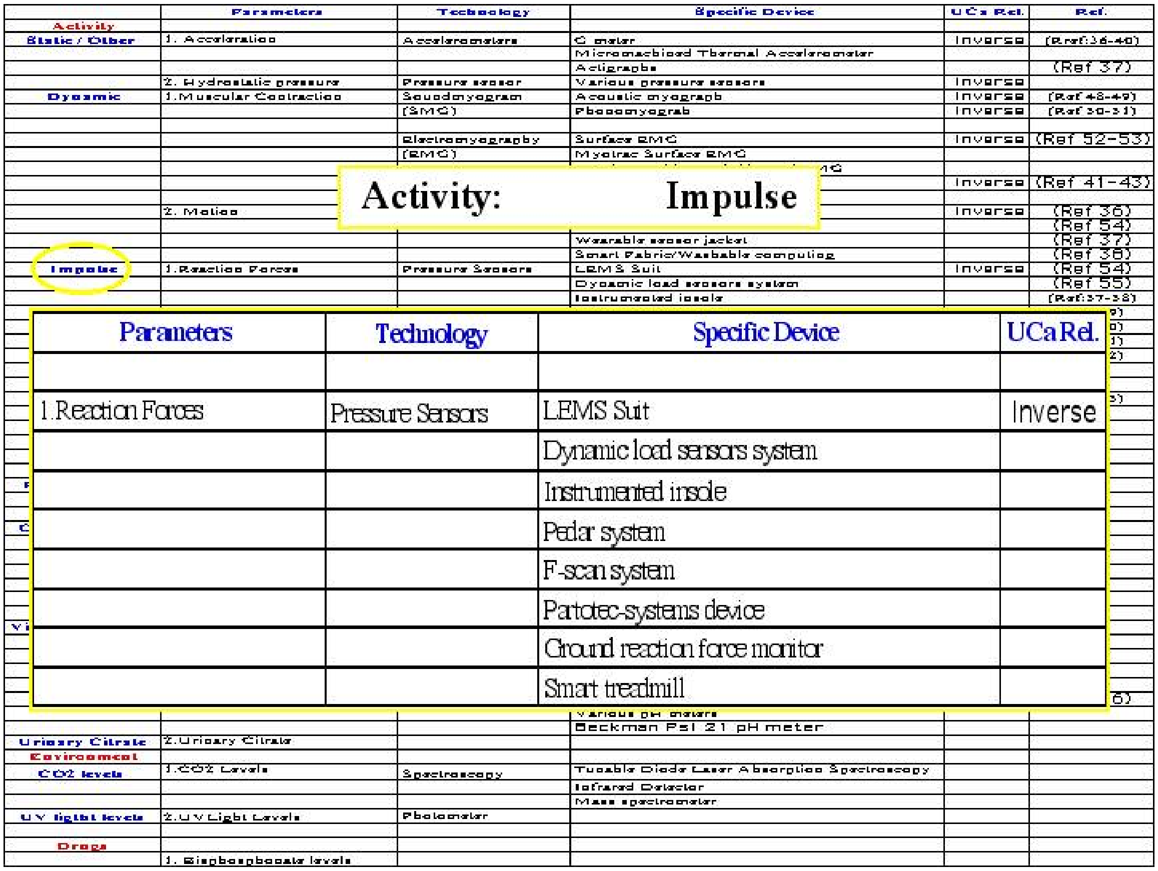
Challenges: How best to quantify the parameters?
How can they be measured?
What are the relationships?

Figure 8. Urinary Calcium Loss Function. Various parameters affect urinary calcium levels, including activity, diet, and environmental conditions. One major challenges in building a countermeasure system is to determine as much as possible about the nature of the relationship between these factors and urinary calcium levels.

C. Sensors

After defining the urinary calcium loss function and determining whether clear urinary calcium relationships exist in the literature, we performed a search for sensors that were available to measure parameters in the bone loss equation. The parameters included activity, diet, drug therapy and the environment. For each parameter, the type of technology was identified and within the technology categories, a list of specific devices that are available for each category was generated.

A sample of this effort is shown in Figure 9. In this case, the parameter from the bone loss equation is impulse activity. This is the reaction force generated when the foot strikes the ground. The technology to make this measurement involves some sort of pressure sensor. A list of devices was generated that shows what kinds of technologies could be used to measure impulse activity for the development of the bone loss prevention architecture. The results for all the parameters are in Appendix A. Some of the sensors that have particular relevance for the bone loss prevention system are discussed below.



Activity: Impulse

Parameters	Technology	Specific Device	UCa Rel.
1.Reaction Forces	Pressure Sensors	LEMS Suit	Inverse
		Dynamic load sensors system	
		Instrumented insole	
		Pedar system	
		F-scan system	
		Partotec-systems device	
		Ground reaction force monitor	
		Smart treadmill	

Figure 9. This graph shows how the different sensors applicable to the bone loss architecture were characterized (see Appendix A for a full listing). In the are of reaction forces, the technology used is some form of pressure sensor. The next column shows the specific devices that have been described that are applicable to the technology area.

Micro-G Project

One device using accelerometers to determine forces that crewmembers make in a weightless environment is the Dynamic Load Sensors System, otherwise called “The Micro-G Project” (*Reference:* http://web.mit.edu/dept/aeroastro/www/labs/DLS/HTMLFiles/index.html). With Professor Dava J. Newman of MIT as one of its leaders, the primary objective of the

Dynamic Load Sensors experiment is to assess nominal crew induced reactions (forces and moments) during spaceflight. Crew motion force measurements are recorded by the DLS for handhold, foot restraint, push-off and landing activities on orbit. This project would provide useful data for developing the system, although it does not measure loading on the subject's skeleton

Actigraphs

Another device that offers potential for measuring activity is the Actigraph (*Ambulatory Monitoring Inc.* http://www.ambulatory-monitoring.com/actigraphs.htm*)*. They are wrist worn devices that provide an unobtrusive means for monitoring activity. Typically, they are used for sleep studies since they can distinguish between times of inactivity (sleep) and the activities of the day. Actigraphs contain a microprocessor and on-board memory. Information can be downloaded to a computer for off-line processing and display. Several models exist but all use the same piezoelectric sensor. The Actigraphs have the benefit of small size and would not interfere with the crew's activities. The disadvantages of the Actigraph are that the data on activity is not specific and no correlation with impulse loads and dynamic activity exist. It is possible, however, that appropriate software might be able to distinguish patterns in the Actigraph data and determine the type of activity undertaken (i.e. treadmill exercise). This area would be a useful area for a Phase II effort.

Wireless pressure sensors

Various pressure sensors would be an integral part of the bone loss/kidney stone prevention architecture. Pressure sensors would need to be on the treadmill and in clothing to help determine activity and loading. An absolute wireless pressure sensor has been developed consisting of a capacitive sensor and a gold-electroplated planar coil (1) Applied pressure deflects a 6 micron-thin silicon diaphragm, changing the capacitance formed between it and a metal electrode supported on a glass substrate. These sensors could be distributed in various locations.

Sonomyography

To determine activity, one other approach is to monitor the activity of muscles. One of the specific devices to do that is the soundmyogram (SMG) (14;18). Through a SMG, muscle sound can be a non-invasive tool to learn about motor unit (MU) activity. According to reports, the suggested generating mechanisms of sound are three: 1). A slow bulk lateral movement of the muscle related to the different regional distribution of the contractile elements, 2). The excitation into ringing of the muscle at its own resonant frequency, and 3). The pressure waves generated by the dimensional changers of the fibers of active Mu's. To work in a bone loss/kidney stone prevention architecture, software would be needed to analyze the signals and convert that data into a representation or activity and skeletal loading.

Electromyography

Electromyography is another approach to measuring muscle activity non-invasively. With this approach electrodes record the electrical activity of muscles (4;5;13). MyoMonitor is a measurement device that uses Electromyography (EMG). NASA, along with other government agencies, has helped Delsys,Inc., of Boston, Massachusetts, develop the MyoMonitor® EMG system —a wearable 4-channel device. Delsys, a spin-off company from the neuromuscular Research Center at Boston University, is also developing an 8-channel version of the MyoMonitor. The MyoMonitor collects data and sends it to a portable device hard-wired to the user and the surface electrodes. (*Reference:* http://www.delsys.com/index.htm) The MyoMonitor reportedly can monitor muscle activity despite rigorous conditions. The system has an easy-to-apply, effective electrode-skin interface that facilitates the uncontaminated detection of EMG signals. The ability to make such recordings, for example, enables experiments aboard the International Space Station for investigating the effect of microgravity on muscle performance. Once collected, data can be transferred to a regular personal computer and analyzed with the EMGworks® software package. As with other devices, the tradeoffs come in providing real-time data collection and a comprehensive analysis programs that can effectively transform the raw (or analyzed) data and incorporate these into the software architecture.

LEMS suit

One unique device is the LEMS Suit. The astronaut dons the suit and then the suit can make measurements on ground reaction forces, joint angles and body movements. The suit tests and takes measurements using a foot-ground interface, joint angles are measured using joint excursion sensors, and muscle activity is determined using surface EMGs. Data is recorded on an Ambulatory Data Acquisition System (ADAS). Although seemingly attractive, at present the suit requires the user to break out of his/her routine to do the testing. For the future this approach might be adapted to be unobstrusive.

Wearable Sensor Jacket

An attractive new device is the wearable sensor jacket (http://www.computer.org/proceedings/iswc/0428/04280107abs.htm*)*. The wearable sensor jacket uses advanced knitting techniques to form fabric stretch sensors positioned to measure upper limb and body movement. The jacket also includes accelerometers able to measure up to 5g accelerations in one axis. These unobtrusive sensors supply abstract information about current activity, but software development would be needed to convert this information into useful data on skeletal loading.

Instrumented Insole

Another very simple device is the Instrumented Insole (http://lifesci.arc.nasa.gov/~rwhalen/fanny.html). Previous studies have assessed physical activity using logbooks, questionnaires, and pedometers. These methods give some indication of the loading history, but fail to consider the true magnitude of the lower limb skeletal forces generated by various daily activities. NASA Ames Musculoskeletal Biomechanics group has developed a portable system which allows determination of long-term histories of the vertical ground reaction force (GRFz), the principal time-varying external force acting on the human body. This system summarizes the magnitude of all GRFz cycles collected over a period of time, as well as the maximum loading and unloading rate occurring during each load cycle. As is the case for the actigraph and wearable jacket, software is needed to convert the data from the device into a useful representation of skeletal loading.

F scan system

A device similar to the one described above is the F-Scan System (http://www.tekscan.com). This device is also an in-shoe system. It is used in the assessment of biomechanical foot dysfunction, with a special focus on the management of plantar pressure distribution for the neuropathic foot. Placed inside the patient's footwear, the system is capable of evaluating dynamic locomotive pressures on the entire plantar aspect of the foot. The F-Scan insoles provide 960 individual sensing points per foot (4 sensors per cm2). The F-Scan sensor is thin (.007") and conforms to most environments. The system is capable of capturing static, walking and jogging events - sampling the complete sensor 165 times per second (316,800 sensors per second). The F-Scan System detects, displays and records plantar forces while they are taking place. For the bone loss/kidney stone prevention system, however, data would have to be collected to assess how skeletal loading could be determined from the data produced by this sensor.

The results of this area of the Phase I effort determined that:

1. Determining urinary calcium and other urinary parameters will not be a limiting factor for the design of a system. Numerous sensors exist, and in the future more capable and smaller sensors are likely to be available.

2. In the future, automated analyses may allow for drug levels to be determined automatically in urine.

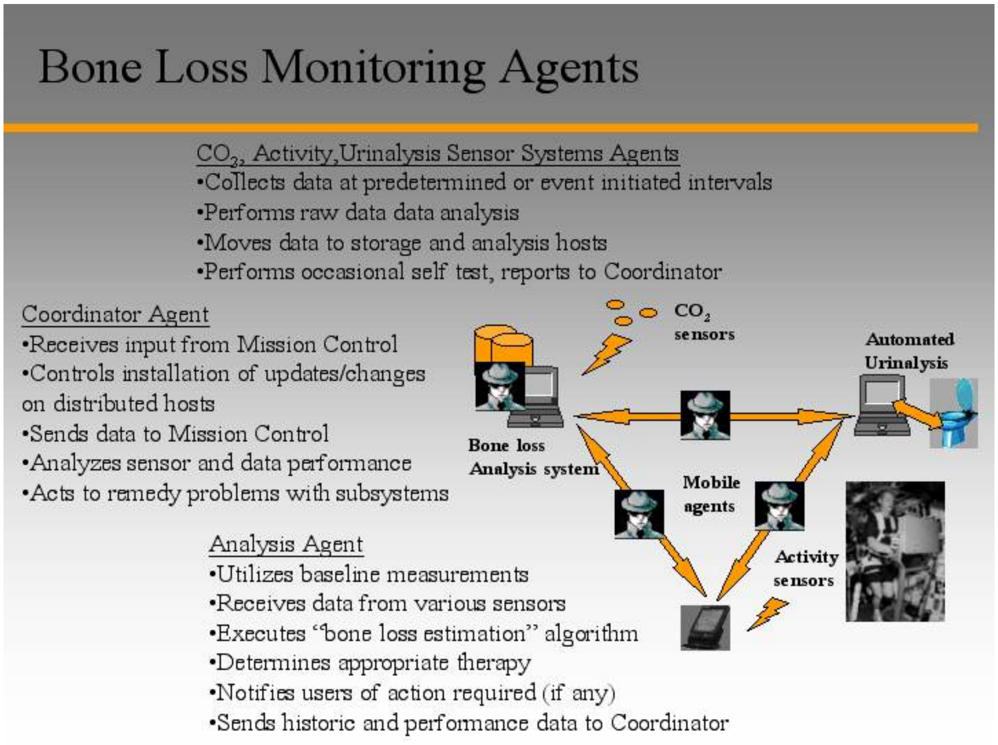
3. Sensors exist now to measure environmental parameters (such as carbon dioxide and UV light), but the relationships to bone loss and urinary calcium are not in place.

4. A fully automated system to determine dietary content does not exist and all systems require some level of crew interaction. Whether diet must be monitored to design an effective system is not known.

4. **The major challenge for the system would be to extract meaningful information on skeletal loading from the sensors that are available now or likely to be available in the future.**

D. Mobile Agents and Analysis Software.

Individual agents are needed to perform the data collection and analysis within the information management framework. Figure 10 depicts one possible breakdown of the agent functionality. There is an agent responsible for interfacing with each type of sensor in the monitoring system, e.g. CO_2 sensors and activity sensors. These agents collect data as required, either on fixed intervals or when an event occurs that triggers the need for data collection. The sensor agents perform filtering of the data and move the relevant information to the analysis agent for further processing. The analysis agent runs the bone loss estimation algorithm using baseline and realtime data and recommends therapy based on the analysis. The coordinator agent is responsible for communication with Mission Control, performs code updates for other agent components and analyzes overall system performance.



Bone Loss Monitoring Agents

CO$_2$, Activity,Urinalysis Sensor Systems Agents
- Collects data at predetermined or event initiated intervals
- Performs raw data data analysis
- Moves data to storage and analysis hosts
- Performs occasional self test, reports to Coordinator

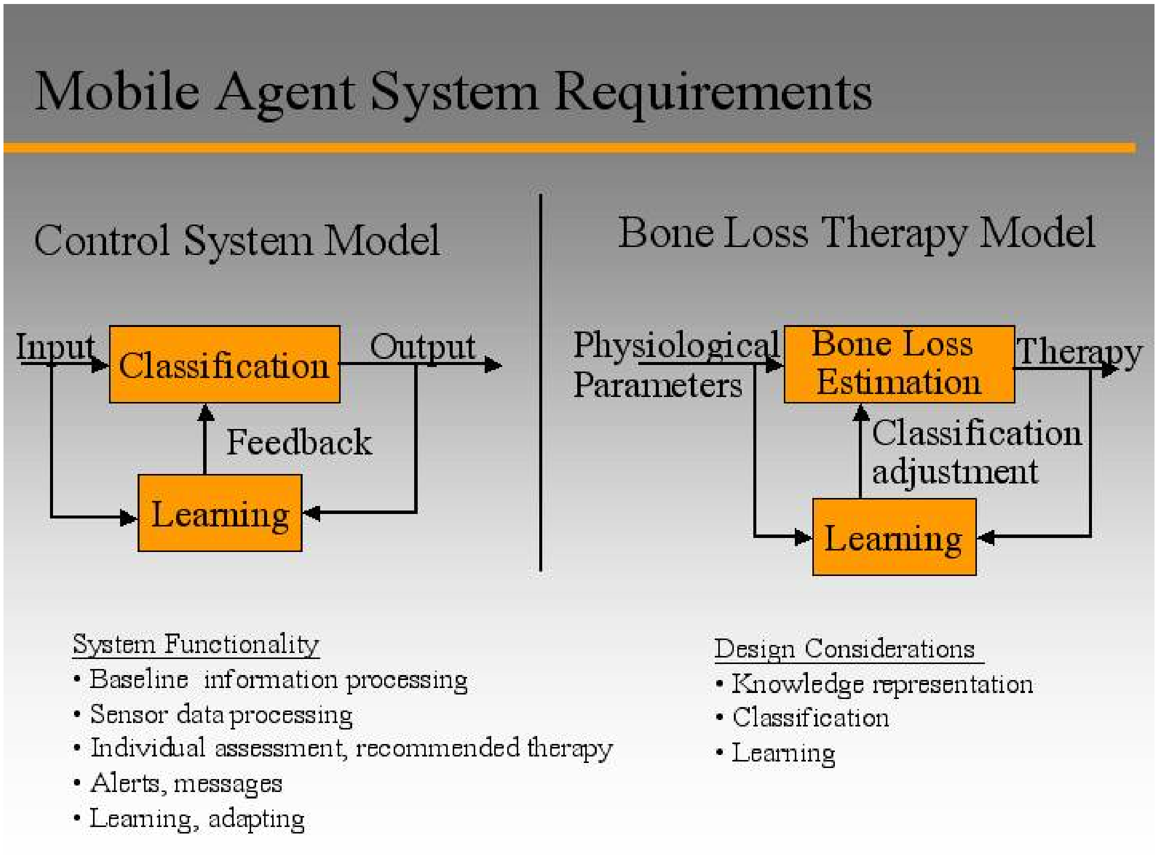
Coordinator Agent
- Receives input from Mission Control
- Controls installation of updates/changes on distributed hosts
- Sends data to Mission Control
- Analyzes sensor and data performance
- Acts to remedy problems with subsystems

Analysis Agent
- Utilizes baseline measurements
- Receives data from various sensors
- Executes "bone loss estimation" algorithm
- Determines appropriate therapy
- Notifies users of action required (if any)
- Sends historic and performance data to Coordinator

Figure 10.Agent functionality can be divided into three major categories: agents responsible for gathering and distributing data from sensors, analysis agents responsible for determining estimates of bone loss and providing recommended therapies, and interface agents needed to coordinate the activities of other agents and communicate with Mission Control.

Integration of each of the individual agent functions into an efficient system is critical to the success of the overall system. Our modeling approach for this implementation is based on an adaptive learning and classification system. Figure 11 depicts an adaptive learning and classification system model where the input is fed into an algorithm where it is processed and classified. The output is generated based on generating a desired state, i.e., the output is intended to change the parameters in the system to achieve a desired goal. The classification algorithm can be improved over time through adaptation. This is accomplished by passing the input and output parameters into a learning algorithm where the overall system goals are used to optimize the classification algorithm.

Also shown in Figure 11 is the adaptive learning and classification system applied to the bone loss monitoring system. In this system the inputs are the measurements of the parameters that affect bone loss. An algorithm is used to make an estimation of bone loss and a therapy is recommended based on the estimation. Over time, both the parameter measurements and the recommended therapy are fed into a learning algorithm to assess overall performance of bone loss estimation and recommendation algorithms. Adjustments to these algorithms can be made of time to achieve the desired result: minimization of bone loss throughout the space flight.



Mobile Agent System Requirements

Control System Model

Input

Classification

Output

Feedback

Learning

Bone Loss Therapy Model

Physiological Parameters

Bone Loss Estimation

Therapy

Classification adjustment

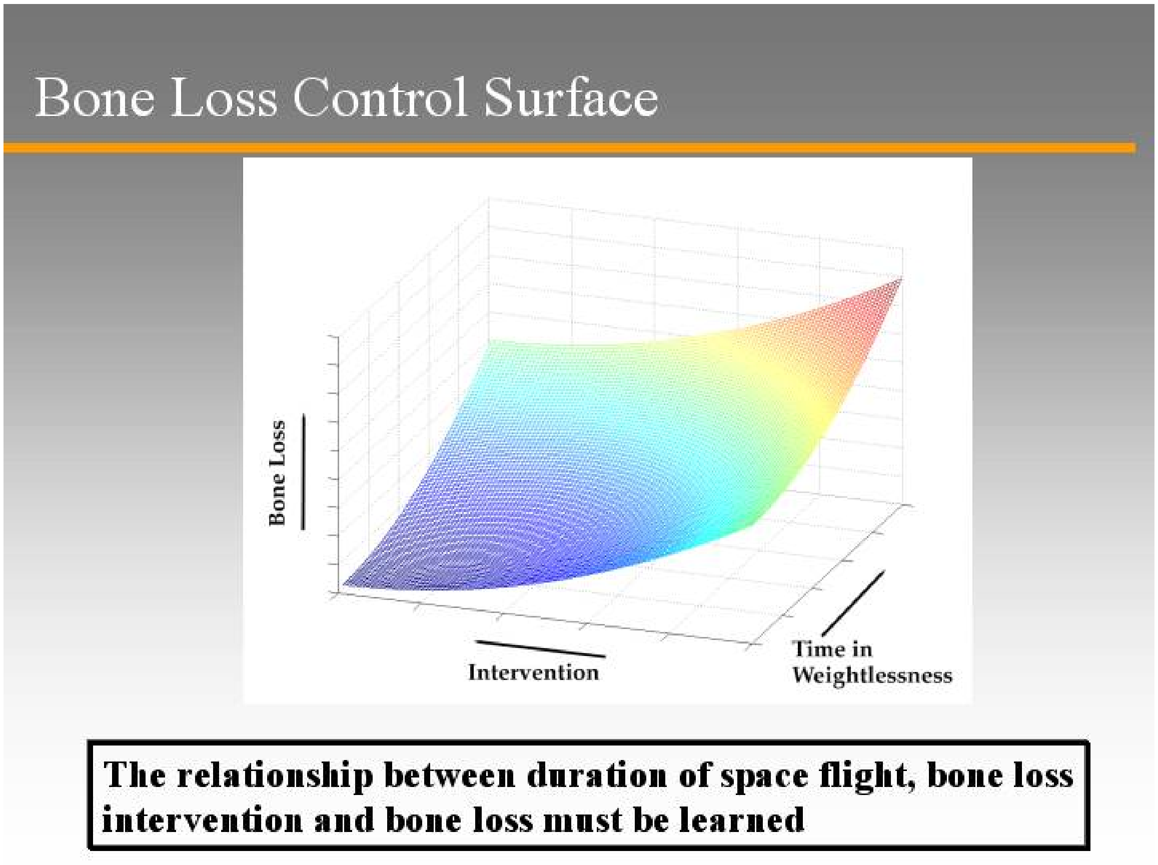
Learning

System Functionality
- Baseline information processing
- Sensor data processing
- Individual assessment, recommended therapy
- Alerts, messages
- Learning, adapting

Design Considerations
- Knowledge representation
- Classification
- Learning

Figure 11. Analysis Software Requirements. The bone loss estimation and therapy recommendation algorithm must adapt to individual crewmember physiology and variability in urinary calcium. Variability may be due to poorly characterized parameters which can affect calcium levels and differences in individual responses to the prevention therapy.

One of the key components of the adaptive learning and classification system is the bone loss estimation and therapy recommendation algorithm. Since the exact relationship between parameters and bone loss is not known the algorithm will need to start with a best guess and adapt over time, as the effects of the recommended therapies are determined. Thus the key to a successful classification algorithm is to learn the surface that describes the relationships between various parameters and bone loss. An example of such a surface is shown in Figure 12. In this figure the effects of weightlessness and intervention to prevent the effects of weightlessness are integrated. . Determining the best set of interventions and details of their relationship to bone loss are major challenges of implementing an effective countermeasure system.


Bone Loss Control Surface

The relationship between duration of space flight, bone loss intervention and bone loss must be learned

Figure 12. Bone Loss Control Surface. The analysis algorithm must be capable of leaning a control surface where the bone loss, interventions, and time in weightlessness are factors.

There are various approaches that can be used to construct an adaptive learning system that can learn control surfaces and be integrated into a classification system such as that shown in Figure 11. Examples of these approaches include Neural Networks, Adaptive Expert Systems, Genetic algorithms and Adaptive Fuzzy Logic. If sample data related to the bone loss factors and relationships can be ascertained, these algorithms can be used to learn the relationships and provide correct classification of data that would be required for the bone loss and kidney stone prevention system.

The analysis performed in this part of the Phase I study determined that:

1. Specific functionality required for the bone loss prevention system can be broken down sufficiently into different categories of agents
2. The model for the analysis software requires an adaptive learning approach to implementation
3. The control surface involving indicators of bone loss, interventions and time in weightlessness needs to be learned by the system
4. Learning the control surface is the most critical and complex part of developing an automated countermeasure program for bone loss prevention.

IV. Summary and Future Work

During this feasibility study we looked at several aspects of designing and implementing an onboard bone loss countermeasure system for long duration spaceflight. Specifically we looked at the feasibility of our overall approach, the relationship between urinary calcium and various parameters which can affect this bone loss indicator, sensors which can be used to acquire measurement data to determine the level of bone loss and interventions, and finally the role of individual agents and the analysis of data that would be required to implement an effective countermeasure recommendation given various baseline and input parameters.

The feasibility of the overall approach of using an agent based information management architecture was assessed by comparing the fundamental system requirements of the bone loss prevention system to those of a military prototype that has been implemented using an agent based information management framework. In general, we have shown that an information management architecture based on mobile agents can benefit long-duration spaceflights for several reasons. New functionalities can be implemented dynamically from earth-based mission control; on-board resources will be more effectively and efficiently utilized (such as on-board communications bandwidth, processor and memory capacities of different on-board computing platforms, earth-to-craft communications resources); crewmember resources will be utilized efficiently since the autonomous nature of the agent software will minimize crew involvement in the countermeasure system operation.

Other crew maintenance applications such as radiation exposure, psychological well-being, and medical care can also be served by implementing and agent-based information management framework. Solutions to these problems would have similar distributed information gathering and analysis requirements. These applications would also be subject to the same limitations in bandwidth and computational power availability.

Automation of crew maintenance systems for these applications could be implemented using networked devices similar to those mentioned for the bone loss application.

In terms of defining a model for bone loss prevention, we first looked at all of the parameters, which can affect the urinary calcium level, which we argue is the most appropriate indicator of bone loss. We have derived a function describing the overall function of these parameters, and have a notion of the general effect of each parameter on the urinary calcium level, e.g., whether and increase or decrease in the measured parameter value will cause a corresponding increase or decrease in the urinary calcium level. What is not known, however, is the specific magnitude of the effect of the parameters on urinary calcium levels. Further study is required to determine which parameters affect urinary calcium enough to warrant their measurement and, at the very least, an estimate of the magnitude of the relationship between the parameter and urinary calcium level.

In our study of sensor technology, we found that many of the sensors that would be needed to collect data to determining bone loss and track the effectiveness of the prevention therapies already exist in some form. For example, the ability to obtain useful data from urinalysis exists, although technology to automate the collection and processing of the urine has not been fully developed. Other parameters, such as skeletal loading, will prove more difficult to obtain since it is likely that this type of monitoring would require invasive sensors.

An analysis of individual agent functionality and analysis of the data that will be used to estimate bone loss and recommend therapies determined that an adaptive learning system model is the most appropriate fit for implementing the analysis functions. The inputs to the system would include baseline data for each crewmember and sensor data to estimate bone loss and track therapies being administered. The output of the system would be the estimated bone loss and a new therapy, if required. Because the effects of various therapies cannot be completely know for each crewmember ahead of time, the system will need to adapt over time to ensure that the therapies recommended are effective at minimizing bone loss. Thus, the success of the analysis system rests with determining which adaptive leaning approach is best suited for this applications, and determining as much as possible about effective therapies for the full range of parameters values that might be seen over the course of the spaceflight.

The overall conclusions from the Phase I study are:

1. Agent-based architectures have been demonstrated for engineering and other applications, but have not been applied to the kinds of noisy data that would be generated in a biomedical application. Existing implementations of agent-based monitoring systems (such as the D'Agent and ActComm projects described in the text, could be modified to meet this needs of an bone loss /kidney stone prevention algorithm.

2. Many studies have been done on calcium metabolism and the factors that affect urinary calcium in the setting of spaceflight are known or can be predicted. Despite this,

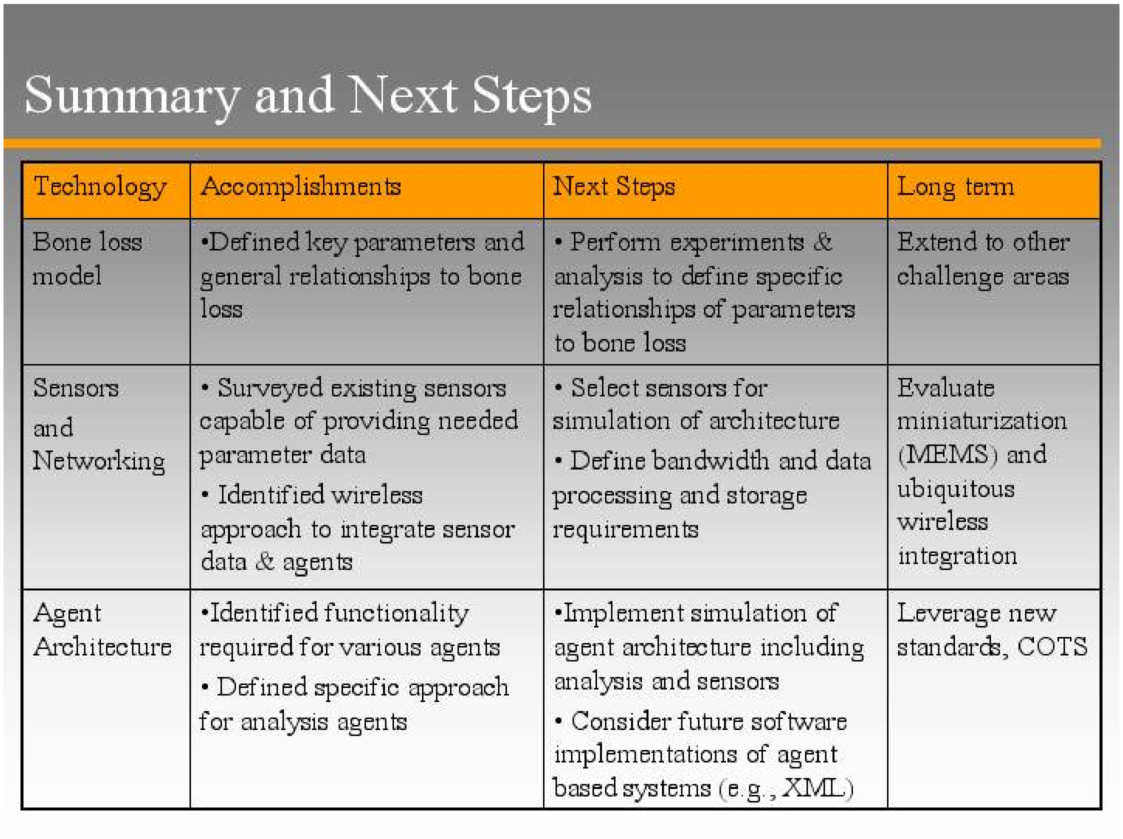
however, the kinds of mathematical relationships that would be need to be defined between urinary calcium and activity, acid-base balance, etc. do not exist due to a lack of specific data.

3. Numerous sensors exist now or are likely to be available in the future that can measure a whole variety of relevant parameters in the urine. The main sensor challenge to developing this system is developing relationships between activity sensors and skeletal loading. These relationships do not exist and are not likely to exist in the future.

In Figure 13 we summarize the accomplishments of this Phase I study and provide a list of recommended next steps for the near and far term. Two recommendations for future study would have a great impact on determining whether this revolutionary approach to countermeasures for long duration spaceflight is realizable:

1. Determining the relationship between urinary calcium and key parameters using both existing data and data collected expressly for this purpose.

2. Developing the adaptive software needed to interpret activity data that will be essential for the bone loss prevention system.



Summary and Next Steps

Technology	Accomplishments	Next Steps	Long term
Bone loss model	•Defined key parameters and general relationships to bone loss	• Perform experiments & analysis to define specific relationships of parameters to bone loss	Extend to other challenge areas
Sensors and Networking	• Surveyed existing sensors capable of providing needed parameter data • Identified wireless approach to integrate sensor data & agents	• Select sensors for simulation of architecture • Define bandwidth and data processing and storage requirements	Evaluate miniaturization (MEMS) and ubiquitous wireless integration
Agent Architecture	•Identified functionality required for various agents • Defined specific approach for analysis agents	•Implement simulation of agent architecture including analysis and sensors • Consider future software implementations of agent based systems (e.g., XML)	Leverage new standards, COTS

Figure 13. Summary of feasibility study and next steps

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Appendix A: Sensors applicable to bone loss/kidney stone prevention architecture

Appendix B: References for Appendix A

Major Factors afffecting Ca balance	**Parameters**	**Technology**	**Specific Device**	**UCa Rel.**	**Time***	**Ref.**
Activity						
Static / Other	1. Acceleration	Accelerometers	G meter	Inverse	?	(Rref:1-4)
(static loading, I.e. standing, sitting)	(ie orientation in real or simulated gravity field)		Micromachined Thermal Accelerometer			
			Actigraphs			(Ref 5)
	2. Hydrostatic pressure	Pressure sensor	Various pressure sensors	Inverse	?	
Notes:						
*Time: I=Immediate, D=Delayed, E=exponential, L=logarithmic, C=linear						

Major Factors afffecting Ca balance	**Parameters**	**Technology**	**Specific Device**	**UCa Rel.**	**Time***	**Ref.**
Activity						
Dynamic	1.Muscular Contraction	Soundmyogram (SMG)	Acoustic myograph	Inverse	?	(Ref: 6,7)
(body movements, not necessarily generating impulse loads)			Phonomyograh	Inverse	?	(Ref: 8,9)
		Electromyography(EMG)	Surface EMG	Inverse	?	(Ref: 10,11)
			Myotrac Surface EMG			
			AT53 Portable Dual-Channel EMG			
		Mechanomyography(MMG)	Mechanomyograph	Inverse	?	(Ref 12-14)
	2. Motion	Accelerometers	Actigraphs	Inverse	?	(Ref 15)
			LEMS Suit			(Ref 16)
			Wearable sensor jacket			(Ref 17)

Major Factors afffecting Ca balance	Parameters	Technology	Specific Device	UCa Rel.	Time*	Ref.
Activity						
Impulse	1.Reaction Forces	Pressure Sensors	LEMS Suit	Inverse	?	(Ref 18)
(movements generating impulse loads on the skeleton)			Dynamic load sensors system	Inverse		(Ref 19)
			Instrumented insole	Inverse		(Ref:20,21)
			Pedar system	Inverse		(Ref 22)
			F-scan system	Inverse		(Ref 23)
			Partotec-systems device	Inverse		(Ref 24)
			Ground reaction force monitor	Inverse		(Ref 25)
			Smart treadmill	Inverse		

Major Factors afffecting Ca balance	Parameters	Technology	Specific Device	UCa Rel.	Time*	Ref.
Diet						
Sodium Intake	1.Dietary Sodium	Bar Codes	Bar Code Reader (BCR)	Direct	?	
		Questionnaire	Food frequency questionnaire	Direct	?	
			Palm Diet Balance	Direct	?	
	2. Urinary Sodium	Ion specific electrode	Various	Direct	?	
		Chromatography	Various	Direct	?	
		Spectroscopy	Various	Direct	?	

Major Factors afffecting Ca balance	**Parameters**	**Technology**	**Specific Device**	**UCa Rel.**	**Time***	**Ref.**
Diet						
Protein Intake	1. Dietary Protein	Bar Codes	Bar Code Reader (BCR)	Direct	?	
		Questionnaire	Food frequency questionnaire	Direct	?	
			Palm Diet Balance	Direct	?	

Major Factors afffecting Ca balance	**Parameters**	**Technology**	**Specific Device**	**UCa Rel.**	**Time***	**Ref.**
Diet						
Calcium Intake	1.Dietary Calcium	Bar Codes	Bar Code Reader (BCR)	Direct	?	
		Questionnaire	Food frequency questionnaire	Direct	?	
			Palm Diet Balance	Direct	?	
	2. Urinary Calcium	Ion specific electrode	Atomic Absorption Spectrophotometry	Direct	?	(Ref: 26)
		Colorimetric analysis	Dionex Ion Chromatographs	Direct	?	
		Chromatography	Perkin Elmer Plasma 40 Emission Spectrometer	Direct	?	
		Spectroscopy	Thermo Jarrell Ash, Smith-Hieftje 22 Atomic Absorption Spectrophotometer	Direct	?	
		Dipsticks	Urinary Dipstics	Direct	?	(Ref: 27)

Major Factors afffecting Ca balance	**Parameters**	**Technology**	**Specific Device**	**UCa Rel.**	**Time***	**Ref.**
Diet						
Vitamin D intake	1 .Dietary Vitamin D	Bar Codes	Bar Code Reader (BCR)	?	?	
		Questionnaire	Food frequency questionnaire	?	?	
			Palm Diet Balance	?	?	
	2. Urinary Vitamin D metabolites	Mass spectrometer	Time of flight mass spectrometer	?	?	

Major Factors afffecting Ca balance	**Parameters**	**Technology**	**Specific Device**	**UCa Rel.**	**Time***	**Ref.**
Acid-Base Balance						
Urinary pH	1.Urinary pH	pH meter	DrDAQ	Inverse	?	(Ref 28)
			Various pH meters			
			Beckman Psi 21 pH meter			

Major Factors afffecting Ca balance	**Parameters**	**Technology**	**Specific Device**	**UCa Rel.**	**Time***	**Ref.**
Acid-Base Balance						
Urinary Citrate	Urinary Citrate	Standard lab assays	Various	Inverse	?	(Ref: 29,30)
		Dipstick	Uridynamics dipsticks	Inverse	?	

Major Factors afffecting Ca balance	Parameters	Technology	Specific Device	UCa Rel.	Time*	Ref.
Environment						
CO2 levels	1.CO2 Levels	Spectroscopy	Tunable Diode Laser Absorption Spectroscopy	?	?	(Ref: 31-33)
			Infrared Detector	?	?	
			Mass spectrometer	?	?	

Major Factors afffecting Ca balance	**Parameters**	**Technology**	**Specific Device**	**UCa Rel.**	**Time***	**Ref.**
Environment						
UV light levels	UVLight Levels	Photometer	Various	Inverse	?	

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