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Effective Presentation of Metabolic Rate Information for Lunar Extravehicular Activity (EVA)

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August 2010

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Executive Summary

A desktop-based simulation of a lunar Extravehicular Activity (EVA) has been developed to study data presentation methods for a crewmember's life-support system. The program, SIM-EVA, was used to compare the effectiveness of several different data presentation schemes.

Results from the tests indicate that an automated metabolic advisor can facilitate improvements in EVA task efficiency. The advisor provides consumable time left estimates, walk-back time estimates, return-back locations, and a task advisory capability that aids a crewmember in real-time route planning during the course of an EVA.

In order to meet EVA stakeholder desires for a robust metabolic advisor capability, it is recommended that the metabolic presentation concepts described in this paper be further extended within a higher fidelity field trial.

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1.0 Introduction

During human exploration of the lunar surface, a suited crewmember needs effective and accurate status information about their life support system so that they may safely and efficiently perform various tasks on the lunar surface. The information must be presented in a manner that supports the real-time consumable monitoring and route planning (and re-planning) that is likely to occur during the course of a lunar EVA.

It is envisioned that information about current levels of consumable life support supplies such as oxygen, water, electrical power, etc., will be provided by a suit-worn, computerized Caution and Warning System (CWS) (EVA OpsCon). The CWS will generate alarms when consumable levels fall below pre-set threshold levels.

Since consumable usage is closely tied to metabolic rate, the CWS system must estimate metabolic rate from life support sensors, such as oxygen tank pressure, carbon dioxide partial pressure, and cooling water inlet and outlet temperatures. As a result, there are requirements related to metabolic rate determination specified for the Constellation lunar suit. The relevant requirements include metabolic rate measurement (HS11015V), crew display (HS11016V), alerting of off-normal values (HS11017V), and telemetry (HS11018V) (EVA ERD).

While CWS-provided metabolic rate monitoring and consumable alarms are crucial to system safety, there is need for additional metabolic analysis and data display. To provide adequate warnings that account for the crew’s location relative to their return point and to factor in return traverse times, a crewmember needs accurate forecasts of consumable depletion rates based upon historic metabolic and consumption rates. According to EVA stakeholder interviews (CxE34001):

The stakeholders strongly support the concept of a “biomed/consumable advisory” capability. This function forecasts remaining EVA consumables, based on metabolic/use rates, and will correlate location information and walking speed to evaluate if a suit has sufficient consumables to transverse from point A to point B. This capability would be used as a planning tool to determine if a crewmember has sufficient consumables to carry out the next task in an EVA timeline.

Advanced metabolic advice is the responsibility of the lunar suit’s Informatics Assembly, which is part of the suit’s Power, Communication, Avionics, and Informatics (PCAI) Subsystem. An operational goal of the Informatics Assembly is to increase crewmember EVA productivity and effectiveness, to improve situational awareness, and decrease the amount of mission support provided by ground-based controllers. The Informatics Assembly provides a suited crewmember with a computing platform, graphical display, user input device, and the data communication links necessary to implement the metabolic advisor and crew interface.

This whitepaper presents concepts for effective display of metabolic information to an EVA crewmember in order to provide efficient, autonomous EVAs.

The work is supported through a NASA PCAI EVA Technology Development Program (ETDP) task.

2.0 Background

A survey of the technology and sensors necessary to determine a crewmember’s metabolic rate is presented in (Dietrich), as well as a review of historical implementations of metabolic rate estimation techniques (e.g., Apollo). During the Apollo program, metabolic rate was determined using three methods: heart rate, oxygen tank pressure, and cooling water temperatures. Ground controllers estimated the remaining level of consumables using the results of these three metabolic rate calculations.

Dietrich recommends using both indirect calorimetric (using data obtained from on-board sensors) and direct calorimetric (using cooling garment inlet and outlet temperature) techniques to determine metabolic rate. The approach is similar to the one recommended by (Kuznetz). Both Kuznetz and Dietrich propose additional measures for metabolic rate determination such as heart and activity monitoring devices.

For the purposes of this study, a simulated lunar metabolic rate is used. The simulated rate is determined from a metabolic cost model presented in (A.W. Johnson). Since the PCAI team is investigating options for the effective display and presentation of metabolic information, and not the metabolic determination itself, the fidelity of the metabolic simulation is not as important as how data is presented to the suited crewmember. For a higher fidelity analysis of suited metabolic rates, refer to information presented in (Dietrich) and (Kuznetz).

Recent information about the integration of metabolic rate information into EVA excursion planning tools has been presented in (Kuznetz), (A.W. Johnson), and (Jessica J. Marquez). The user interface implemented by Kuznetz is quite extensive, with the capability for voice recognition and voice synthesis. Johnson and Marquez describe systems that determine efficient paths between defined waypoints on a map. Metabolic cost estimates are provided for the determined path. The Johnson system provides a method to determine return-home paths from user specified points along a path, as well as a three-dimensional rendering of the path overlaid on the local terrain. Marquez uses a flat two-dimensional visualization that determined both computer-generated and user-assisted path routes based upon an objective cost function. Interestingly, Marquez found that subjects that used the computer-generated paths had larger cost errors and took longer to perform than those that used user-assisted ones. They also scored lower on a test of situational awareness. The increased reliance on automation had decreased the subject’s ability to understand their current state.

The work explained here does not address computer-optimized EVA path generation, but instead focuses on providing metabolic rate information in a manner that maintains situational awareness within the processing, display, and electrical power constraints that are likely on the lunar EVA suit. There is an important role for optimizing path planners and three-dimensional visualizations in support of EVAs, but they may be constrained to operate from within a base or habitat module where appropriate computing and display resources are available.

3.0 System Description

The basic concept of the system proposed here is to measure increases in task efficiency, during a simulated EVA, which can be attributed to an automated Metabolic Advisor algorithm. The objective of the EVA Metabolic Advisor algorithm is to conserve valuable suit resources including oxygen, water, etc. The Metabolic Advisor must not only provide projections about consumable usage rates, but must also display the information in a manner that allows a suited crewmember to make intelligent choices about traverse directions and work levels.

A measure of the effectiveness (task efficiency) of the Metabolic Advisor is obtained by comparing the number of waypoints reached during an EVA both with, and without, the Advisor. To test the Advisor, the task efficiency demonstrated in a set of simulated EVA traverses is evaluated. Each traverse starts at an initial base location, passes through a series of waypoints, and then returns back to base. Various tasks may be performed at particular waypoints along the traverse route. Task efficiency is measured by comparing the number of waypoints visited during the course of each traverse.

3.1 Operational Concept and Requirements

The functional capabilities of the Metabolic Advisor are listed below, in increasing order of complexity. This approach supports an implementation where simple functions are performed on a highly reliable CWS assembly, while more complex operations are implemented within a separate Informatics Assembly.

During the course of an EVA the metabolic advisor shall:

1. Determine quantities remaining of oxygen, power, and water and predict the time remaining for each consumable. A TIME LEFT value is displayed to the crewmember based on the limiting consumable. The TIME LEFT value doesn't take into account the crewmember's location or heading on the lunar surface.
2. Determine a walk-back time. This is the amount of time needed to perform a contingency walk-back from the crewmember's current location. This time will be determined by consumable usage rates and crewmember position relative to the base (as provided by navigation).

3. Calculate a return-back point. This is the location where the crewmember has to turn- around and returns to the base. This location will be determined by consumable usage rates and crewmember position relative to the vehicle (provided by navigation). To support a worst-case scenario, the return-back point should be based on the projected consumables needed for the crewmember to do a walk-back to the vehicle. So, when the return-back point is reached during the EVA, the TIME LEFT calculated should be equal to the walk-back time, with some margin to spare. The system should provide the crewmember with some advanced warning before the return-back point is reached. Instead of returning to the vehicle, the crewmember could do an oxygen recharge or battery change-out, assuming that those capabilities are provided on the rover. Or, the crew can drive in the rover to a worksite location closer to the vehicle. Moving closer to the vehicle would effectively extend the return-back point to a time point later in the EVA. Basically, as long as the TIME LEFT calculation is greater than the walk-back time from that specific location, EVA tasks can continue.

4. Provide a task advisory capability. The capability is simple: provide the means for the crewmember to determine if there are enough consumables to travel to another location in order to perform a task. Basically, if the crewmember is currently at point A on the surface, the advisor supplies information about whether it is possible to safely reach point B, either by walking or driving in the rover. To do that, the Advisor needs to look at consumable levels, usage rates, and navigation data for the traverse from point A to point B while at the same time determining if there are enough consumables to support a walk-back to base from all locations in the path.

3.2 Implementation

The computer program developed for evaluation of the metabolic advisor is known as SIM-EVA. SIM-EVA is programmed in the Java programming language and is targeted for desktop computing platforms, but designed so that the Metabolic Advisor concepts could be ported to an embedded system for field trials. Note that the appropriate scale factors were modified in SIM-EVA to keep each simulated traverse to about 15 minutes in length.

The system software was developed using guidelines specified by (NASA 7150.2) and supporting NASA GRC Flight Software Branch's effort to achieve a Capability Maturity Model Integration (CMMI) Maturity Level 2 rating.

3.2.1 User Interface

An image of the SIM-EVA program, as shown when it is initially opened, is provided in Figure 1. The SIM-EVA display is divided into four regions as identified in Figure 1.

1. **SIM-EVA Controls**: This region provides user input to control operation of the EVA simulation.

2. **SIM-EVA Metabolic and Consumable Status**: This region provides user feedback about the current levels of consumables, as well as metabolically-determined EVA information, such as an estimate of the time left for the most limiting life support consumable (e.g., oxygen), and an estimate of the walk-back time to the lunar base. The life support simulator developed for SIM-EVA provides an estimate of oxygen only, so the statuses of the other consumables are inactive.

3. **Historical Path Information**: This region shows the vertical elevation of the crewmember's path.

4. **Terrain Map**: This region provides a visual map of any safe haven (base), excursion waypoints, traverse paths, and topographical terrain. The terrain information is shown in both a color-coded gradient format (dark red are elevation peaks, dark blue are valley floors) and as contours of equal elevation. The current location of the EVA crewmember is shown with a small astronaut icon.

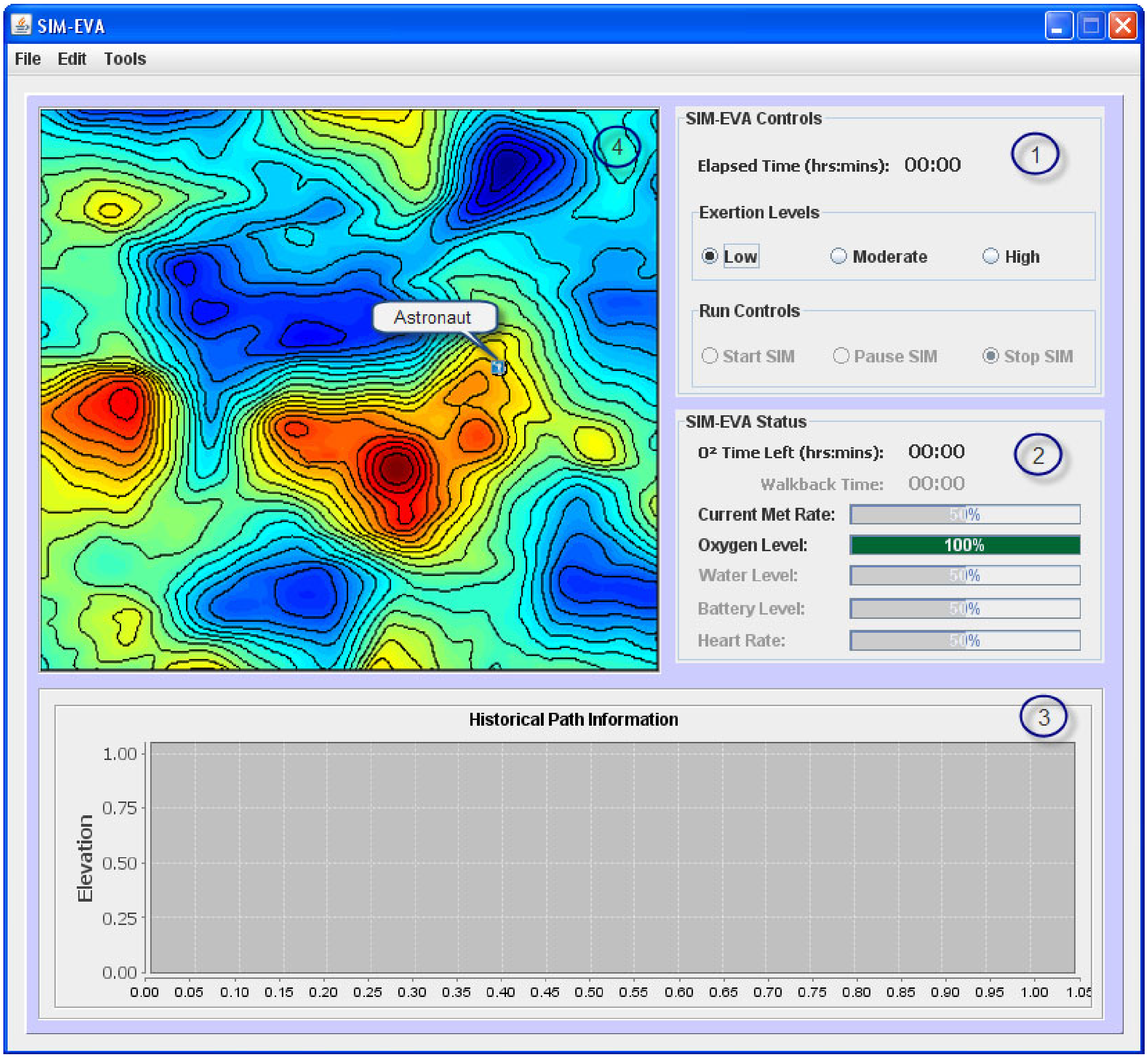

Figure 1.—SIM-EVA main screenshot.

3.2.2 EVA Metabolic Cost Model

Since SIM-EVA is a primarily a tool to study the display and presentation of metabolic and life support information, the model used to determine that metabolic cost of each EVA segment is fairly simple, requiring few computing resources. A visual representation of the model is shown in Figure 2. In the figure, connections between the model components are depicted using three different line types. Thick lines connect those functions that provide basic life support usage projections such as TIME LEFT. Thin lines represent more advanced functionality. Dotted lines show future enhancements to the model.

Individual components of the metabolic cost model are described in more detail below.

3.2.2.1 Operational Terrain Constraints Component

Compares a proposed path provided by the user with terrain constraints. The default constraint for the maximum allowable slope that may be traversed is ±15°. If no terrain limitation for a proposed path exists, then further evaluation of the traverse path is enabled.

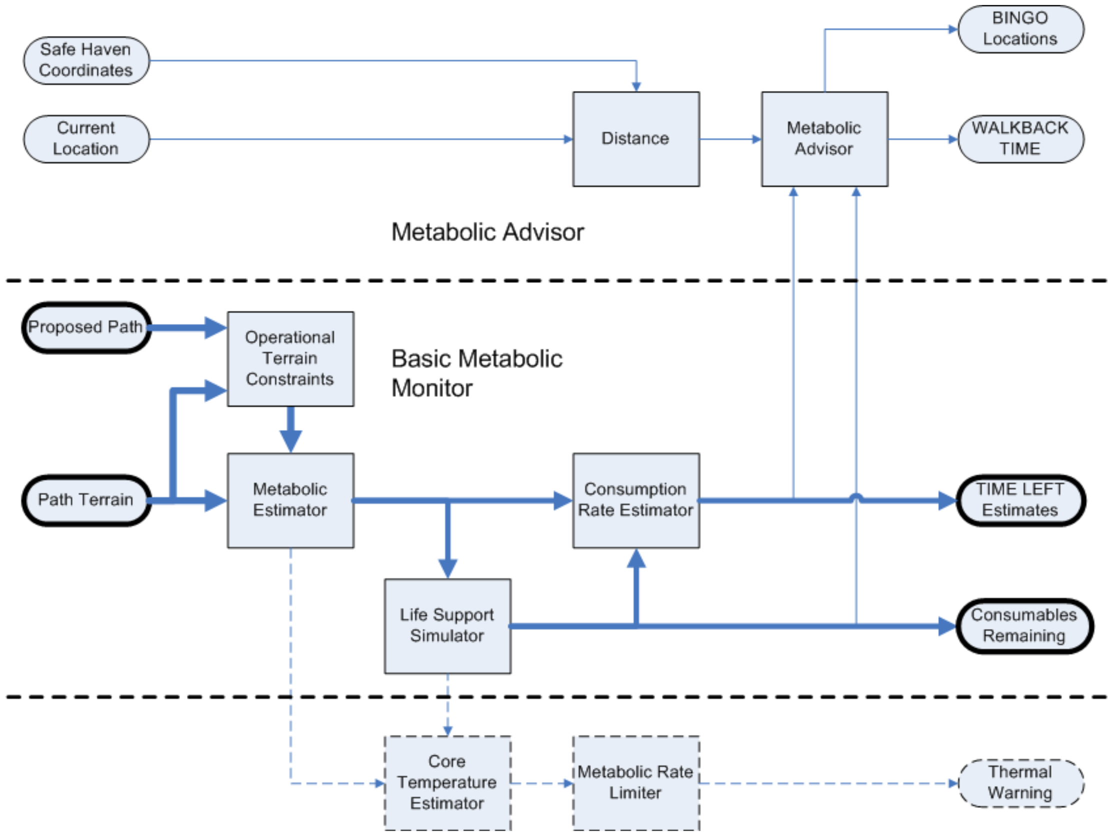

Figure 2.—SIM-EVA metabolic cost model.

3.2.2.2 Metabolic Estimator Component

The Metabolic Estimator determines the metabolic energy expenditure of a particular EVA path. It is dependent upon a crewmember's physiological characteristics (e.g., mass). For SIM-EVA, a standardized set of physiological characteristics was chosen.

The Metabolic Estimator determines metabolic cost from Apollo 14 mission data using a method identified by (Marquez) and pictured visually in Figure 3.

3.2.2.3 Life Support Simulator Component

The Life Support Simulator determines the consumable levels remaining given the initial levels and the estimated metabolic rate.

3.2.2.4 Consumption Rate Estimator Component

The Consumption Rate Estimator provides an estimate of the future consumption of life support supplies given a history of a crewmember's metabolic rate and path.

3.2.2.5 Distance Component

The Distance block determines the geographical distance between the crewmember's position and the closest safe haven.

3.2.2.6 Metabolic Advisor Component

The Metabolic Advisor provides estimates of WALKBACK TIME and BINGO locations to the crewmember. The Advisor does not, at the present time, consider surface terrain features, obstacles, elevations, or slopes, but only considers historical consumption and trends.

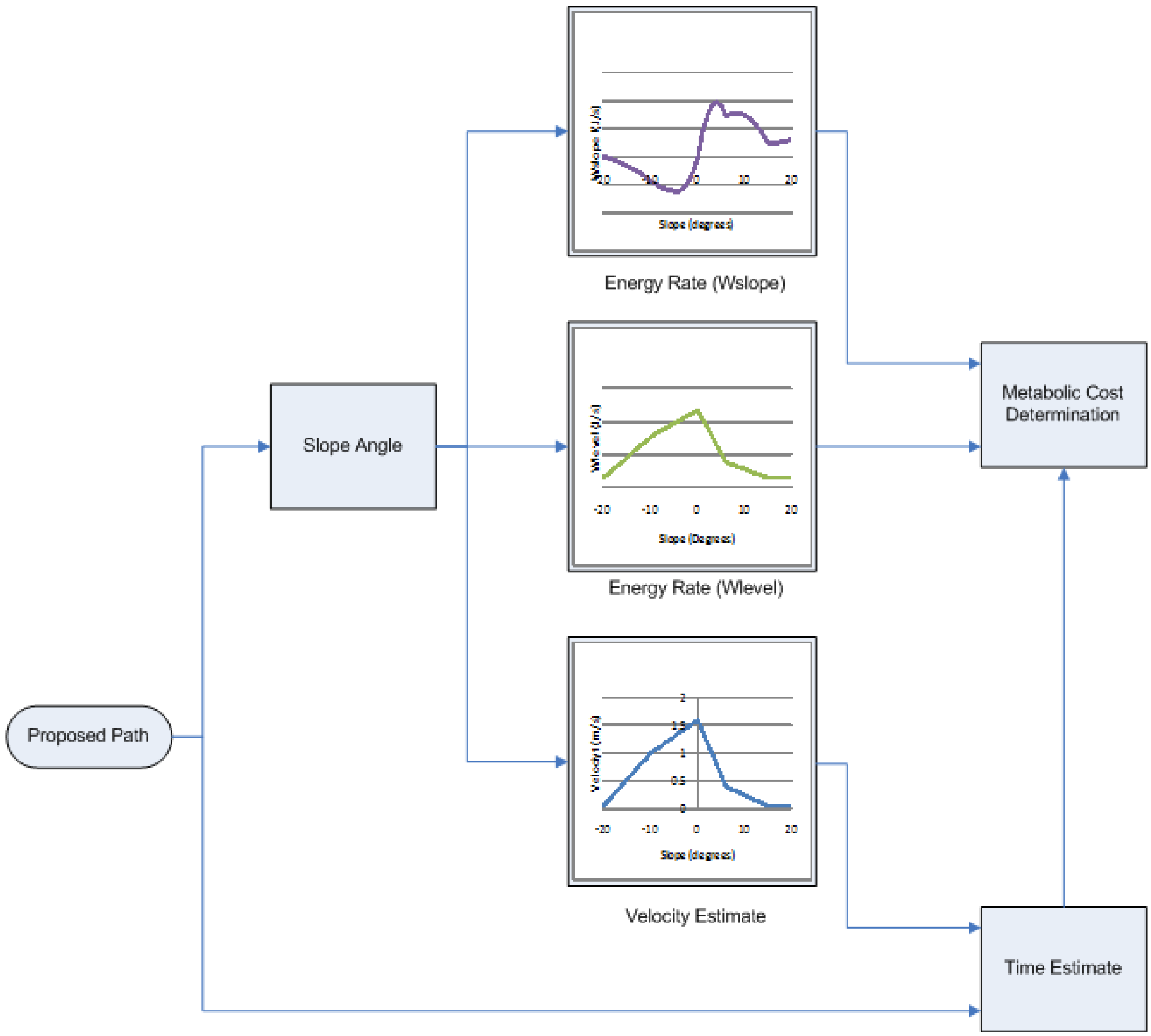

Figure 3.—Metabolic estimator.

3.2.3 Presentation of Consumable and Metabolic Advisor Information

Seven presentation levels of metabolically derived information are available on SIM-EVA. Higher levels provide increasingly detailed amounts of metabolic information. The levels are:

1. **Consumable Quantities**: Display the existing levels of consumables in the suit life support system. Currently, only the oxygen level is simulated.
2. **Low Consumable Warnings**: When the levels of consumable fall below alarm thresholds, the color of the corresponding level display changes from green (nominal) to yellow (warning) and then to red (alarm). The current threshold levels for these alarms are set at 50 and 25 percent of capacity.
3. **Time Remaining**: Display estimate of EVA time remaining for the limiting consumable.
4. **Walk-Back Time Display**: An estimate of the amount of time necessary to return to the nearest safe haven.
5. **Maximum Range Display**: Display an estimate of the distance that may be traveled before consumables are completely depleted via a *range circle* display.
6. **Bingo Range Display**: An ellipse indicating an estimate of the maximum distance that may be traveled on existing levels of life support consumables while still maintaining enough consumables to return to the nearest safe haven.

7. **Safety Bingo Range Display**: An ellipse showing an estimate of the maximum excursion allowed before an operationally defined safety margin is reached. The safety margin is currently set to 10 percent. An EVA could extend to the indicated location and return to the safe haven before the consumables are depleted to this level.

Note: Items 6 and 7 provide a rudimentary task advisory capability. Waypoints within the bingo ellipse may be safely reached, while waypoints outside the bingo line may not.

The metabolic information is shown, as displayed in SIM-EVA, on Figure 4. Other non-metabolic information, such as movement restrictions due to slope outside the operational range, is shown in dialog boxes as in Figure 5.

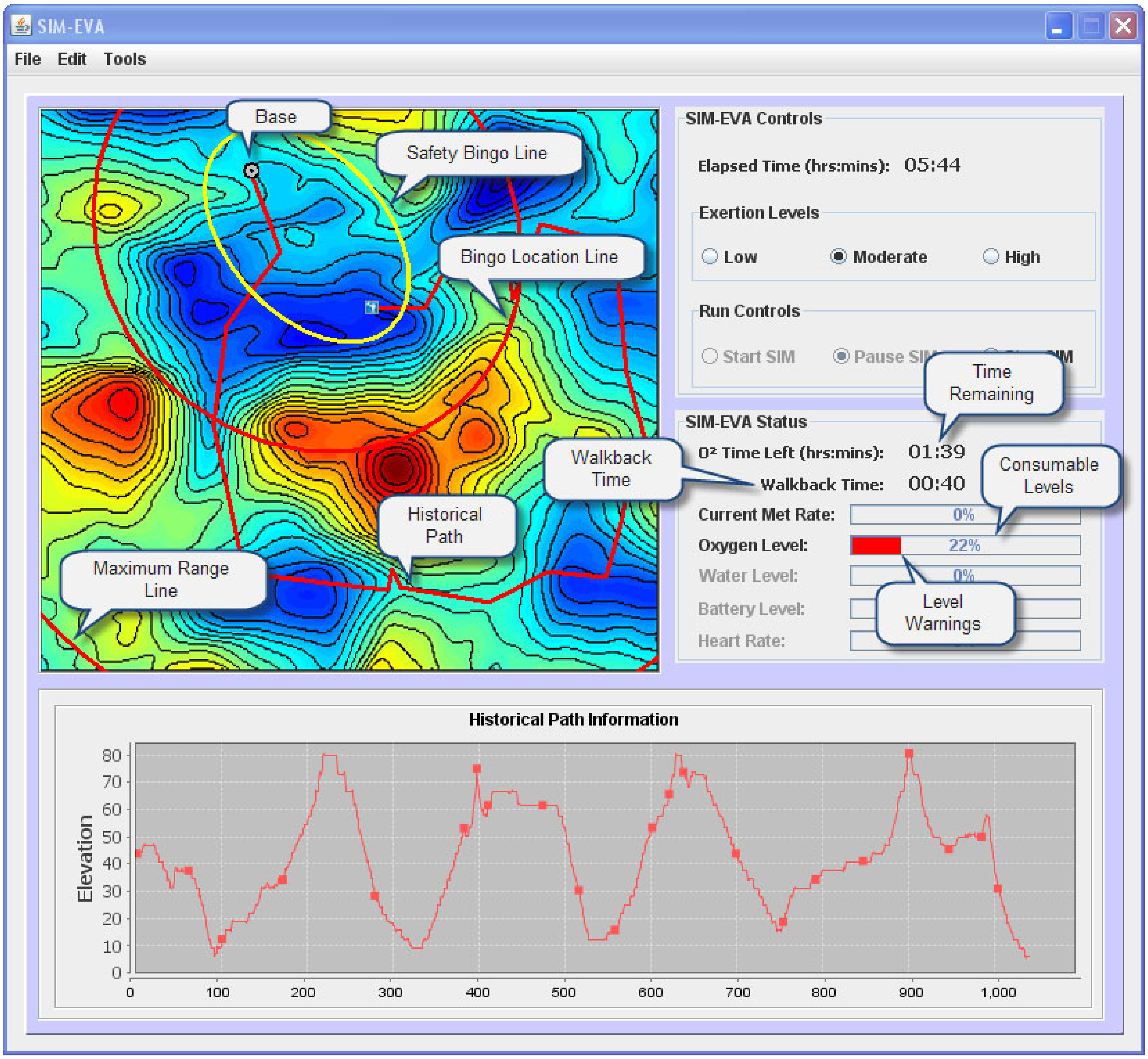

Figure 4.—Metabolic information display.

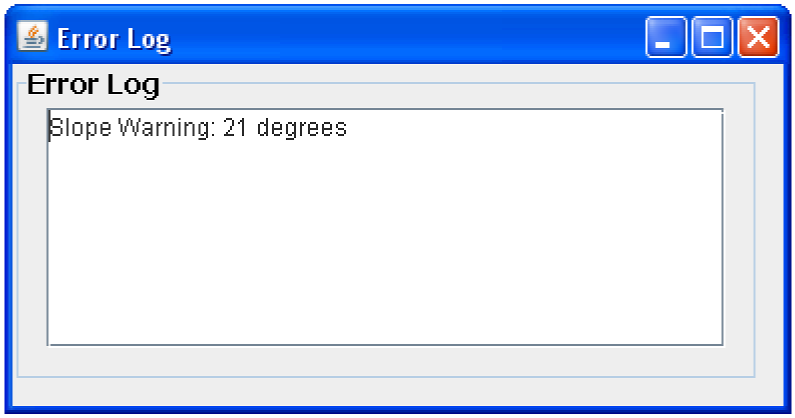

Figure 5.—SIM-EVA warning dialog.

4.0 EVA Simulations

A series of EVAs were simulated using the SIM-EVA tool. The terrain for all simulations was chosen to have a variety of topographical features, including hill peaks and valley bottoms, as shown in Figure 6.

4.1 Assumptions and Limitations

For the purposes of these simulations, it is assumed that the simulated terrain in the immediate vicinity of the lunar base is relatively unexplored. There is little *a priori* knowledge about detailed terrain features at a resolution below what could be obtained from a lunar mapping satellite. In other words, for these simulations, crewmembers do not know the optimum path between two locations. They may estimate paths from the provided terrain map, but only know the detailed geography of a location after it has been visited.

It is also assumed that the suit has limited display capabilities, so consumable information must be displayed in a concise and effective manner to the suited crewmember.

EVA-SIM does not currently account for resting metabolic rates (i.e., there is no consideration provided for a user to rest at their current location). In the current implementation, no consumables are used unless the crewmember is moving over terrain.

4.2 EVA Simulation Using the Basic Metabolic Monitor

Basic consumable information (presentation levels 1 to 3) is provided to a user by the Basic Metabolic Monitor. The capabilities of the Basic Metabolic Monitor are similar to those of the Space Shuttle Extravehicular Mobility Unit (EMU) Display and Control Module (DCM) (JSC-20957). At the beginning at each simulation, the crewmember is located at the lunar base, as shown in Figure 1.

A user progresses through a simulation by selecting the direction and length of the next segment of traverse. Users were instructed to reach as many waypoints as possible before returning safely to base. Initially, users were not able to plan their path effectively, since they had little experience with the depletion rate of their consumables correspondent with their traverse path. Occasionally, users completely depleted their consumables before they were able to return to base as shown in Figure 7. In Figure 7, the historical route taken by the user is shown in red. Colored circles indicate waypoints. The astronaut icon marks the ending location of the EVA. The base is shown at the beginning of the historical path. In the trial of Figure 7, note that the EVA elapsed time is approximately eight hours and there are zero hours of oxygen remaining.

Users reported that they primarily used the terrain map and oxygen level display to plan their EVA path. They did not report using the TIME LEFT value to determine turn-around points, probably because they did not have enough experience to use this value effectively.

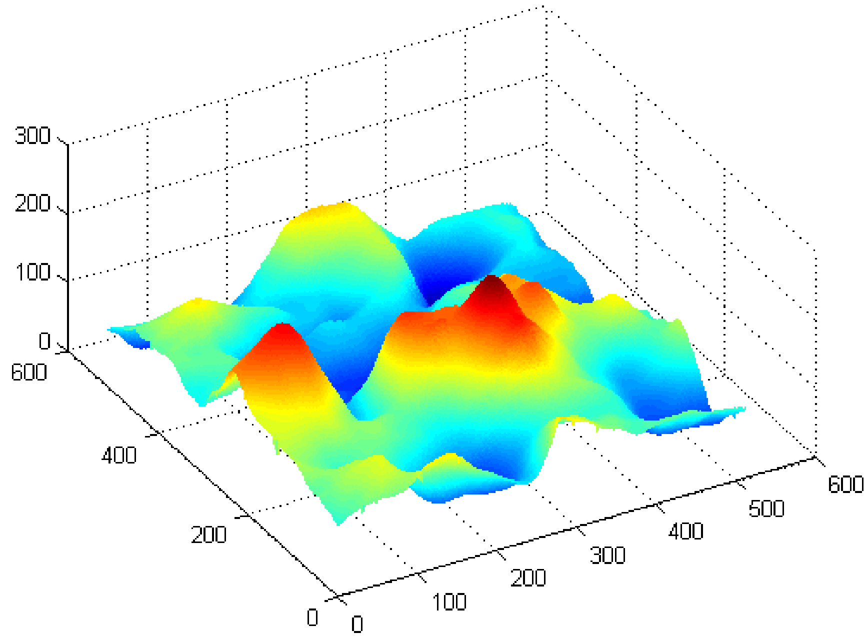

Figure 6.—Simulated lunar terrain.

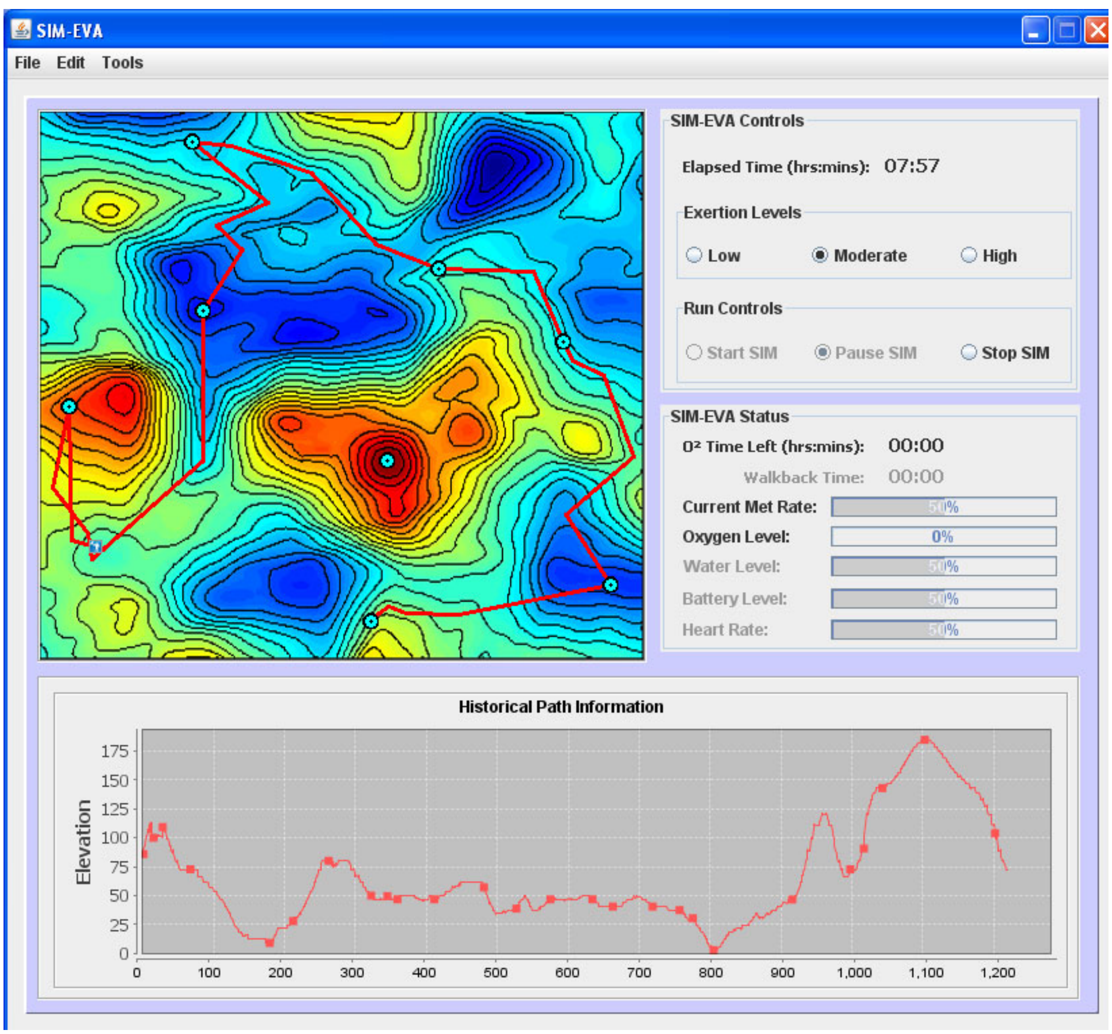

Figure 7.—Sample simulation showing consumable depletion.

4.3 EVA Simulation Using the Metabolic Advisor

The Metabolic Advisor provides more advanced metabolic rate information (presentation layers 1 to 5) than is provided by the Basic Metabolic Monitor. In order to function, the Advisor requires knowledge about the geographic location of the both the crewmember and the closest safe haven. A key value determined by the Metabolic Advisor is the walk-back time estimate. A crewmember should turn around and return to base, at the latest, when the walk-back time display is equal to the time left display. Since the walk-back time value assumes travel in a straight-line path back to base, it is difficult for a user to forecast consumption along paths that are not directly back to base. The WALKBACK value provides little intuition about paths that deviate from a direct return path. As an illustration, view the trial depicted in Figure 8. The user has 29 percent of oxygen left and a WALKBACK time estimate of 25 minutes. Is there enough oxygen to reach waypoint A or B and return safely to base? It is difficult to discern using only the TIME LEFT and WALKBACK TIME values

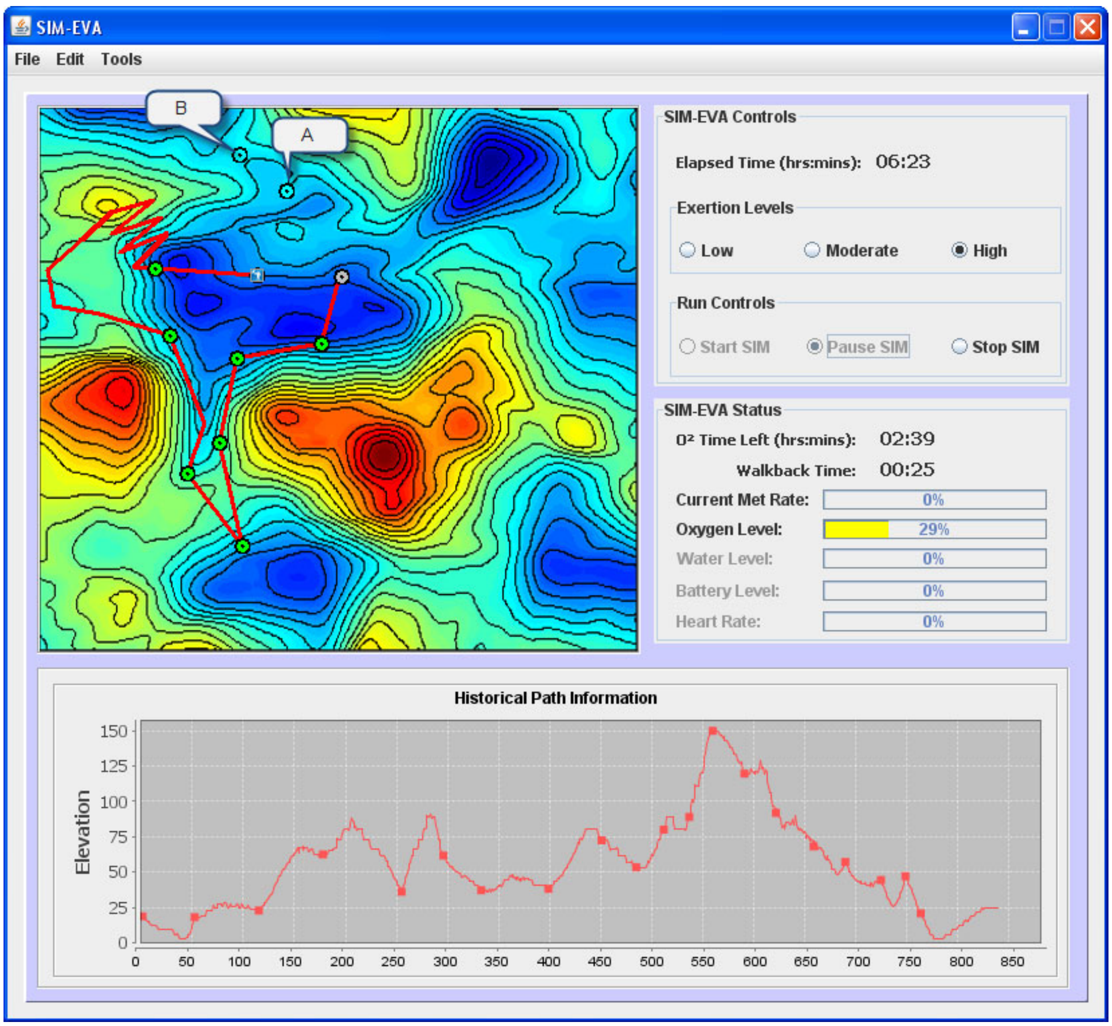

Figure 8.—EVA simulation with WALKBACK time.

4.4 EVA Simulation Using the Augmented Metabolic Advisor

Additional capabilities were added to the Basic Metabolic Advisor in order to increase its usefulness. Estimates of the maximum bingo (turnaround) and safety bingo locations provided by the augmented Advisor are overlaid on the terrain map as shown in Figure 4 and Figure 9. These overlays make path-planning decisions easier for the user. In Figure 9, the red ellipse indicates the maximum bingo location. The user should be able to travel up to the bingo location and still have enough consumables to return safely to base, albeit with no safety margin. For an additional safety margin, travel within the yellow bingo line provides a reserve consumable level of 10 percent when base is reached.

Figure 9 depicts the same EVA scenario as Figure 8, except that the bingo locations are shown. Since Waypoint A is within the safety bingo (yellow) line, and the terrain is relatively flat, it can safely be reached. Once Waypoint A is reached, Waypoint B's location in relation to the bingo line can be evaluated, as shown in Figure 10. Figure 10 shows that Waypoint B can also safely be reached. After Waypoint B is reached, following the return path directly back to base results in a remaining oxygen level of 13 percent.

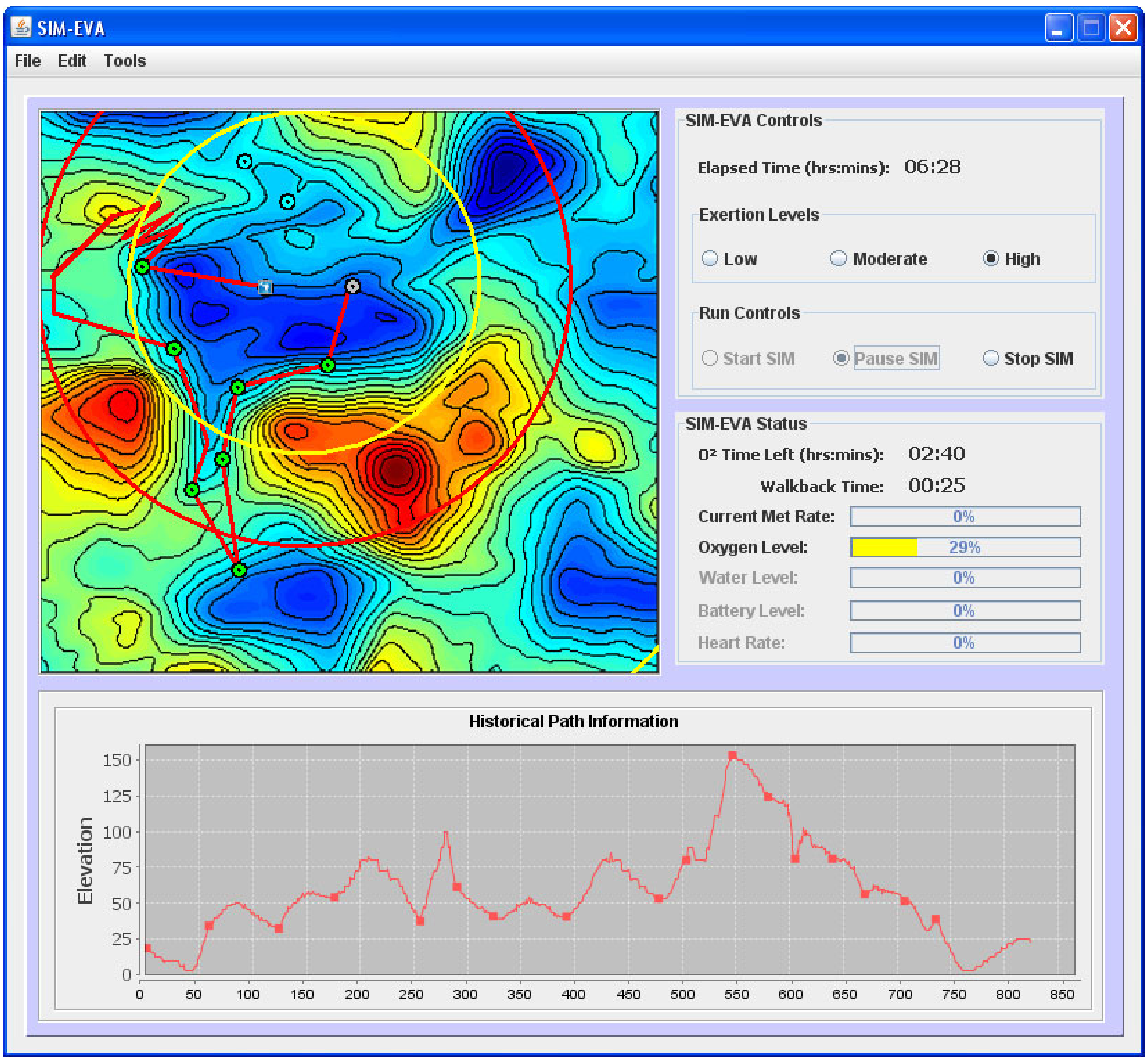

Figure 9.—EVA simulation with BINGO locations.

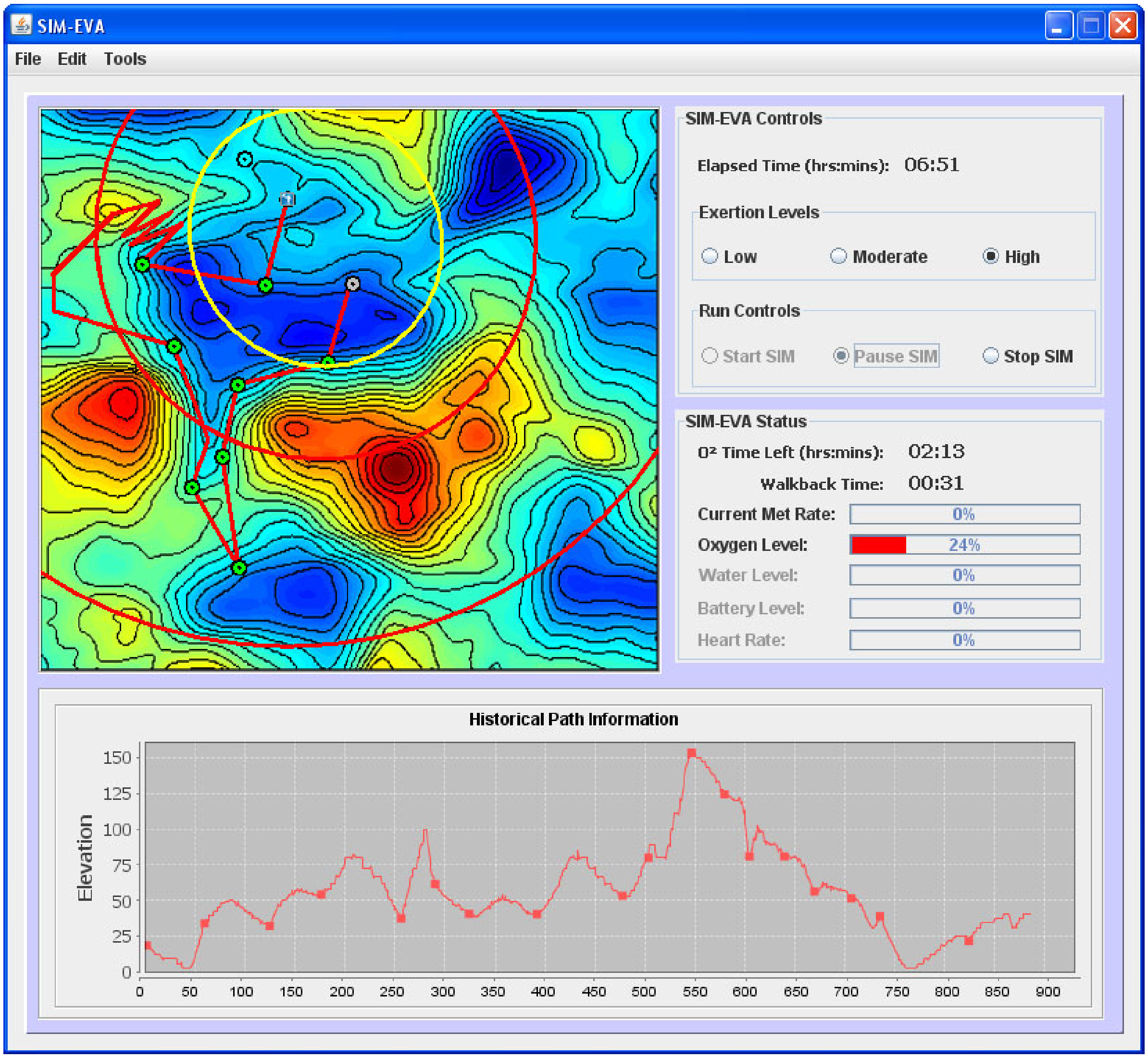

Figure 10.—Waypoint A reached.

5.0 Results and Discussion

A series of tests were performed with the terrain shown in Figure 6. Twenty waypoints were randomly distributed across the terrain. The location of the EVA starting point (the base) was also randomly located. Over a large number of runs, any effect on performance due to the locations of the waypoints and base average out.

Users performed half the tests with information from the Basic Metabolic Monitor only (with capabilities similar to the Space Shuttle EMU DCM), and half were performed with the Augmented Metabolic Advisor. Users were experienced in using the SIM-EVA program.

Results from the tests are provided in Table 1.

TABLE 1.—SIMULATION RESULTS

Test type	Average number of waypoints reached	Average amount of oxygen remaining at conclusion (%)	Average time left (hr:min)
Basic metabolic monitor	10	11.1	1:03
Augmented metabolic advisor	11	13.7	1:14
Percent improvement	10%	22%	17%

Results from these tests show an improvement in task efficiency (the number of waypoints reached) due to the additional information provided by the Augmented Metabolic Advisor versus the Basic Metabolic Monitor. There is a more significant improvement in the amount of consumables remaining at the end of simulation, with a corresponding increase in safety margin.

6.0 Summary and Forward Work

Improvements to the SIM-EVA have been suggested. Some users experienced difficulties being trapped by steep ravines or inclines that were of too small a resolution to see clearly on the map. They expressed a desire to zoom within the terrain map.

The most commonly used features, as expressed by the users, were the oxygen level gauge and the bingo range indicators. The TIME LEFT value display seems to have less utility since there is no easy correlation to distance. On the Space Shuttle or Space Station, where the limiting consumable TIME LEFT value is also displayed, this deficiency is unimportant, since EVAs are always performed within a relatively short (fixed) distance from a safe haven.

Several users proposed integrating metabolic and terrain cost information together and showing on the user display. There was also a desire to show areas of extreme slope or obstacles as “keep-out” areas on the terrain map. These suggestions can be investigated further in future versions.

Another improvement would be the integration of a core body temperature simulator and thermal advisor into SIM-EVA as envisioned in Figure 2.

Finally, the capability to consider the metabolic costs of performing specified tasks at each of the EVA waypoints should also be included in future versions.

It is anticipated that this work will undergo field trials to test the advisor in more realistic scenarios. For the field version, metabolic rates will be derived from a test subject using methods suggested by (Dietrich) and (Kuznetz) (e.g., indirect calorimetry) rather than the simulated metabolic rates generated by SIM-EVA.

7.0 Conclusions and Recommendations

The results of this work indicate that there is value in providing effective presentation of metabolic information by means of an automated metabolic advisor. Features of the advisor that should be incorporated include: time left estimates, walk-back time estimates, return-back locations, and a metabolic forecasting capability that aids crewmembers in real-time EVA route planning.

Appendix A.—Acronyms and Abbreviations

CMMI	Capability Maturity Model Integration
COTS	Commercial Off-The-Shelf
CWS	Caution and Warning System (Assembly)
Cx	Constellation (Program)
DCM	Display and Control Module
EMU	Extravehicular Mobility Unit
ETDP	Exploration Technology Development Program
EVA	Extravehicular Activity
GRC	Glenn Research Center
N/A	Not Applicable
PCAI	Power, Communications, Avionics, and Informatics

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
During human exploration of the lunar surface, a suited crewmember needs effective and accurate information about consumable levels remaining in their life support system. The information must be presented in a manner that supports real-time consumable monitoring and route planning. Since consumable usage is closely tied to metabolic rate, the lunar suit must estimate metabolic rate from life support sensors, such as oxygen tank pressures, carbon dioxide partial pressure, and cooling water inlet and outlet temperatures. To provide adequate warnings that account for traverse time for a crewmember to return to a safe haven, accurate forecasts of consumable depletion rates are required. The forecasts must be presented to the crewmember in a straightforward, effective manner. In order to evaluate methods for displaying consumable forecasts, a desktop-based simulation of a lunar Extravehicular Activity (EVA) has been developed for the Constellation lunar suite’s life-support system. The program was used to compare the effectiveness of several different data presentation methods.

15. SUBJECT TERMS
Man/system technology and life support; Computer programming and software

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