ADAPTING SYSTEM-OF-SYSTEMS ENGINEERING FOR THE ADVANCEMENT OF THE MARS EXPLORATION PROGRAM

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Introduction: The current data infrastructure of the Mars Exploration Rover (MER) mission revolves around the availability of communication windows between Earth-based science teams, engineers, etc. With the upcoming 2009 Mars Science Laboratory (MSL) mission and the next-generation planetary missions to Mars this data infrastructure must be modified to account for the large increase and eventual data-rich environment scientists and engineers will be working with in the next 2-3 years.

System-of-Systems (SoS) is a methodology for viewing networks of individual systems that are made and act independently but need to function together for a common goal. Concurrently, System-of-Systems Engineering (SoSE) is the implementation of those solutions, tools, and task-oriented groups used to resolve the reconstruction of the original system. The modification of the data infrastructure of MER to fit the future needs of MSL and later missions requires such a methodology to achieve the robust use of resources, time-management, and science team efforts.

The purpose of this paper is three-fold: (1) to introduce this adaptation of systems engineering to the MSL data network, (2) show the beneficial implications of group work between science and engineering teams, and (3) to show possible optimization techniques used for future modeling of both SoSE protocols and resource management.

Motivation & Methology: The exploration programs sponsored by NASA have always incorporated multiple-level networks that are mostly homogeneous by their disciplines but as a whole perform tasks that are diverse among the separate groups involved. To accomplish their mission objectives these teams must have the ability to investigate, implement, and adapt to changing situations within planetary exploration operations [1]. The Mars Exploration Program consists of current and future missions that rely on the ability of previous network arrangements for communication, data transfer, and flight operations. The information framework for these missions do not have a central "adaptability protocol" and cannot be readily changed if necessary, making real-time decisions on a large scale almost impossible. In order for such an ability to exist there needs to be an upgradable or modifiable system template that all missions (both manned and robotic) conform to. Thereby allowing Earth-based mission support (geology science teams, rover engineers, etc.) the capability in-flight and essentially in-situ alteration of tasks and data flow. System-of-Systems allows for such an outline to be build and for future estimates of design flaws (disruptors) and benefits ("sweet spots") to be modeled.

System-of-Systems nomenclature. While there is little consensus to a general SoS model our approach uses the terminology and framework (Fig. 1) from DeLaurentis et al, 2006 [2] to confine the phases of internal and external factors occurring in a system [3] and that change over time.

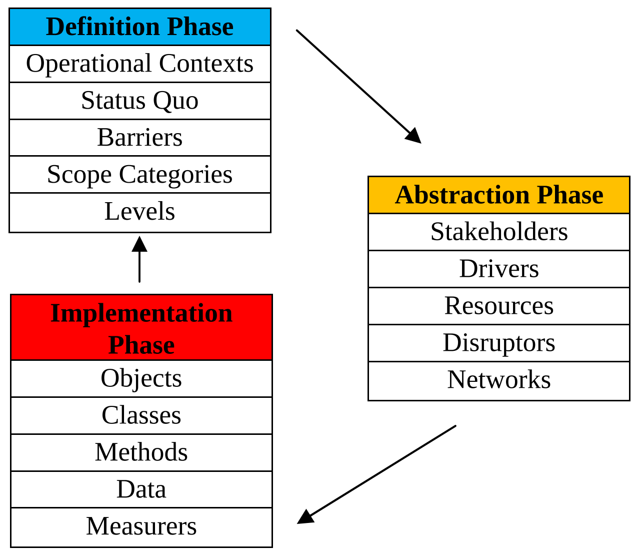

Figure 1: Three-phase SoS structure as described by DeLaurentis et al, 2006 [2] showing the modeling features within a developing problem. This configuration will always be cyclic in nature due to the uncertainty of future behavior.

In adapting SoS structure to meet the science needs of the MSL mission we need to redefine the nomenclature to include normally separate disciplines together. Part of this redefinition comes from the work done by Mishkin et al. [4,5] while the new features being worked on put emphasis on the geology science team acting as "intellectual stakeholders" as well as the workers in terms of data analysis – giving faster turnaround time with regard to transmission of data.

The structure and power source of MSL will allow for multiple science planning sessions (SOWG, APAM Mast/Sub, CAM, etc) to occur in one sol due to the data-rich environment the science teams will be on and the ability of MSL to essentially work around the clock. To alleviate the need for a staffed science and engineering team to work through non-traditional hours (such was the case during MER's primary mission) some concepts have been devised to increase work flow and create fluid movement of data transmission in such an environment.

- Emphasis on science theme groups will incorporate engineers solely for that group. This will assist in prioritizing sequences and science team requests (Fig. 2).
- On-site engineers will get familiarized with the geologist's "scientific data interest" and vice-versa for the engineer's tasks to allow for real-time decision making without having to wait for a specific payload leader or science team member to carry out an assigned task.
- These smaller groups will also represent 2-3 instruments of similar type on the rover relating to the geologic use of said instrument. The groups will assess the use of their instruments given the current target-rich setting that the rover is in.

Group work & informed decisions.. A large part of changing the data infrastructure and overall process of MSL is the human and overall team aspect of the equation. MER has been nothing short of a complete success in terms of science data return and engineering initiatives because every component had a well informed person able to decide the best course of action behind it. To ensure the best possible choices were performed engineering sequences, science targets, etc. were confirmed many times over. When the capability of the MSL rover gives the science and engineering teams huge amounts of data their needs to be capable people at the receiving end who can process, analyze, assess, and implement tasks at a fast rate in order to make the best use of the mission's timetable. To increase the amount of capable people without losing integrity to their original assignment, the idea of "knowledge communities" within the entire MSL operation gives people the ability to make low-medium level informed decisions [6]. Moreover as mission time goes on and the systems themselves evolve, these knowledge bases will become a focal point and allow any team member to gain experience in another's discipline or task assignment with great simplicity [7]. These information centers can be highly beneficial to newcomers on the mission and provide updates for task changes and reassignments.

Multidisciplinary optimization & resource allocation. An efficient way to model the available time within science planning and to help make the optimal decision is to use specific optimization algorithms [8] that treats your science payload as levels of importance in the respective environment that those tools would be used in, hence their significance. While many linear programming based algorithms might be used an initial test was conducted using the Branch and Bound algorithm [9] for deciding which science operations to conduct in three sample environments. The final results gave a 94-100% efficient use of time management. This type of decision support on a multidiscipline mission would prove valuable to confirm which instruments should be used and how the science team manages appropate time slots.

References: [1] Rader, S., Kearney, M., McVittie, T., Smith, D. (2006) *AIAA Space 2006-5723*. [2] DeLaurentis, D.A., et al. (2006) *AIAA Space 2006-7248*. [3] Sindiy, O. and DeLaurentis, D.A. (2007) *AIAA Space 2007-6527*. [4] Mishkin, A.H. Limonadi, D., Laubach, S.L., Bass, D.S. (2006) *IEEE Robo. & Autom. v13, 2, 46-53* [5] Mishkin, A.H., et al (2007) *Proc. IEEE Aerospace*. [6] Garrett, S. and Caldwell, B.S. (2002) *Beh. & Info. Tech. 21,5 359-364.* [7] Caldwell, B.S. (2005) *Avia., Space, & Env. Med. v76, 6*. [8] Crossley, W.A. (2004) *MIT Engineering Systems Division.* [9] Shestak, V, et al. (2008) *J. Para. & Distrib. Comp. v68, 4, 410-426.*

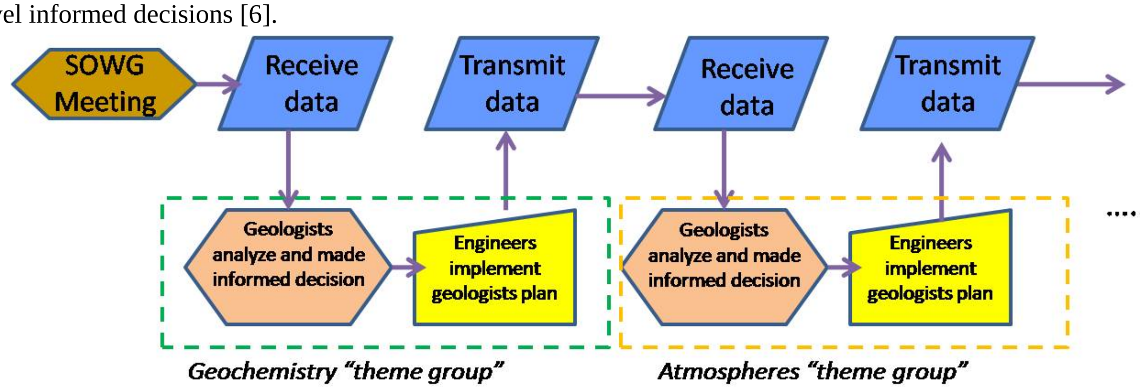

***Figure 2:** One possible restructuring of data flow for the 2009 MSL mission. Given the high level communication ability and in-turn data-rich environment, future Mars operations will need to rely on a fast and fluid informed decision making process that allows for rapid succession of data products. Using the System-of-Systems (SoS) approach to modify the current data infrastructure will allow us to pinpoint "sweet spots" as well as "landmines" to optimize the system architecture and later model future estimates of success.*