Evaluation of Human and Automation/Robotics Integration Needs for Future Human Exploration Missions

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Abstract— **NASA employs Design Reference Missions (DRMs) to define potential architectures for future human exploration missions to deep space, the Moon, and Mars. While DRMs to these destinations share some components, each mission has different needs. This paper focuses on the human and automation/robotic integration needs for these future missions, evaluating them with respect to NASA research gaps in the area of space human factors engineering. The outcomes of our assessment is a human and automation/robotic (HAR) task list for each of the four DRMs that we reviewed (i.e., Deep Space Sortie, Lunar Visit/Habitation, Deep Space Habitation, and Planetary), a list of common critical HAR factors that drive HAR design.**

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1. INTRODUCTION

Future exploration missions will extend human presence beyond low earth orbit (LEO). There are a variety of possible mission objectives, durations, and destinations. These NASA missions are described through proposed Design Reference Missions (DRMs). NASA DRMs evolve and change over time as a result of technology advancements, participating organizations, and funding priorities. This paper focuses on providing a systematic assessment of the critical factors and needs associated with future effective human and automation/robotic integration (HARI) as delineated by the NASA DRMs.

The Human Research Program (HRP) funds research efforts aimed at mitigating all the Human Health and Performance Risks, including the Risk of Inadequate HARI Design. As such, the assessment conducted focuses on a set of DRM categories, defined in the HRP Requirements Document [1]. These HRP-relevant DRM categories are summarized in Table 1. For example, Low Earth Orbit (LEO) DRM category includes International Space Station 12-month long missions (ISS12) and Commercial Suborbital missions. Deep Space Habitation DRMs include Lagrange Point 1 or 2 (L1/L2) Habitation and Asteroid Visits. Future missions beyond LEO were included in this assessment, namely Deep Space Sortie, Lunar Visit/Habitation, Deep Space Journey/Habitation, and Planetary Visit/Habitation.

2. ASSESSMENT METHOD

In order to conduct a systematic assessment of the future critical HARI factors and needs, the first step was to identify all the human-automation-robotic (HAR) tasks delineated by the NASA DRMs. Each DRM was reviewed and analyzed by our team of HARI experts from across different centers and with varied backgrounds. The HAR tasks are those activities (or tasks) identified in the DRMs, where

Table 1: Human Research Program Design Reference Mission (DRM) Categories

DRM Categories	Mission Duration	Gravity Environment	Radiation Environment	Earth Return
Low Earth Orbit (LEO)	6 months	Microgravity	LEO – Van Allen	1 day or less
Low Earth Orbit (LEO)	1 year	Microgravity	LEO – Van Allen	1 day or less
Deep Space Sortie	1 month	Microgravity	Deep Space	< 5 days
Lunar Visit/Habitation	1 year	1/6 G	Lunar	5 days
Deep Space Journey/Habitation	1 year	Microgravity	Deep Space	Weeks to Months
Planetary Visit/Habitation	3 years	Fractional	Planetary	Months

operators in spaceflight (i.e., astronauts) or on Earth must complete using some automated or robotic system. Additionally, the type of integration and/or interaction required to complete the task was determined or assumed by the evaluating team.

Based on the HAR tasks, a set of factors was derived. Figure 1 summarizes our assessment process. This "bottoms-up" approach was selected in order to ensure that the identified critical HARI factors and needs came from the future DRM requirements. Additionally, it was important to compare the needs across DRMS. In order to achieve a systematic evaluation for all DRMs, an assessment framework was outlined. A challenge to developing a consistent assessment across multiple mission architectures was that each DRM is composed of different mission elements and systems. In order to have an assessment that would be useful for comparisons *across* the DRMs, a set of generic system classes needed to be defined. The framework leveraged generic system classes (describe subsequently in this paper). Using this framework, the various DRMs were consistently evaluated.

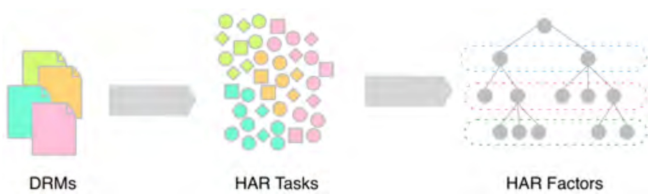

Figure 1: Assessment process overview

Background information about each DRM included published papers, reports, and presentations [2-9]. For this assessment, the documentation for the Planetary Visit/Habitation DRM was derived from Mars DRMs. Since some DRMs are less mature than others, additional references were included in the assessment. NASA's Technology Roadmaps [10] and NASA-sponsored workshops or documents were reviewed with respect to future operations of advanced automation and robotic agents [11,12].

3. HUMAN-AUTOMATION-ROBOTIC TASKS, FACTORS, AND SYSTEMS

Often task analyses are completed in order to evaluate human-machine interactions in systems. Traditionally, task analysis is defined as "the study of what an operator (or team of operators) is required to do, in terms of actions and/or cognitive processes, to achieve a system goal" [13]. Since assessment focused on mission concepts and architectures (as described by the DRMs), the identified tasks are high-level descriptions. Assuming further specificity or task decomposition would not have been beneficial as the mission architectures are described at high levels. It would have been too speculative to identify HAR task decompositions at the subtask or cognitive decision level. Hence, the identified HAR tasks remained at the descriptive level.

All HAR tasks were considered—those performed by crew in flight and by ground controllers on Earth. Tasks are classified into four categories in order to facilitate the DRM assessment. The categories, further described below, are Spacecraft Guidance, System Management, Robotic Operations, and Mission Planning.

Spacecraft Guidance Tasks

The first category of HAR tasks is Spacecraft Guidance. These HAR tasks are dynamic control tasks of space vehicles. Traditionally, these are the tasks that are considered "piloted" tasks: operators are required provide inputs to the spacecraft, which in turn quickly affect state of the spacecraft vehicle, such as its position, orientation, or velocity. Depending on the amount of spacecraft automation or whether in an emergency scenario, executing these HAR tasks frequently requires manual interaction. For these HAR tasks, operators would likely interface with spacecraft systems such as attitude guidance control, and determination, and propulsion. For example, landing the Apollo Lunar Lander Module would be considered a Spacecraft Guidance HAR task. While there may be other dynamic HAR tasks that require hand-eye coordination, Spacecraft Guidance tasks were limited to large space vehicles that are typically, though not necessarily, pressurized vessels.

The following HAR tasks were considered Spacecraft Guidance Tasks:

- Ascent, which includes launching from Earth or from any other planetary body with a significant gravity well.
- Entry/Descent, which includes re-entry to Earth or approaching another planetary body with a significant gravity well. It also includes descent to a planetary body with an atmosphere, such as Mars.
- Landing, the flight phase subsequent to entry and descent, including landing on Earth (on land or sea) or another planetary body with significant gravity well.
- Docking/Undocking, which includes the attaching and detaching one spacecraft from another.
- Maneuver/Reboost/Rendezvous, which includes execution of finite, short dynamic changes in spacecraft attitude, typically used during approaching other spacecraft or planetary bodies with very small gravity wells.
- Drive/Navigate, which includes maneuvers on or near a planetary body that require continuous dynamic changes in spacecraft vehicles. This set of tasks could be considered a subset of Maneuvers/Reboost/ Rendezvous.

System Management Tasks

The second category of HAR tasks is System Management. Initially, the HAR tasks identified under this category were Fault Detection, Fault Isolation, and Fault Recovery. Collectively, these tasks became a set for Fault Detection, Isolation, and Recovery (FDIR). This task set, as the name implies, requires monitoring spacecraft systems, identifying system failures, isolating the root cause, and resolving or working around the off-nominal condition. FDIR is particularly important in complex, automated systems, and is viewed as a critical need in future human-robotic missions [14]. Typically, FDIR is more akin to state process control and typically (though not necessarily) has longer response times. For example, off-nominal failures may lead to emergencies that need to be addressed immediately by astronauts. On the other hand, one of the main responsibilities of ground flight controllers is to monitor and respond to sub-system issues as they arise, correcting and addressing them in a timely-manner. Moreover, these HAR tasks are essential for pre-deployed spacecraft, subsystem, and robotic assets, as automated checkout of habitats and vehicles is an assumed mission capability [15]. For these HAR tasks, operators would likely interface with spacecraft systems such as thermal, power, communications, command and data handling, and environmental and life support control systems.

Robotic Operations Tasks

The third category of HAR tasks is Robotic Operations. This set of tasks focuses on the operations of advanced automation and robotic agents. The NASA DRMs mention various types of highly autonomous systems, but tend to not be specific on the tasks. Additional references [10,11,14, 16] were leveraged to list a comprehensive set of Robotic Operations Tasks. For instance, Pedersen et al. (2003) provides a set of functionalities for future robotic agents: assembly, inspection, maintenance, human assistance, mobility, instrument deployment, and science planning and perception. Similarly, Mishkin et al. (2007) outlines functionality for robotic systems that assist crew in assembly, habitat construction, sample return, science exploration, and human assistants. Included in this set of Robotic Operations Tasks is functionality attributed to other highly autonomous systems, which differs from System Management because these tasks do not focus on FDIR.

The following HAR tasks are considered Robotic Operations Tasks:

- Complex assembly tasks:
  - Capture and Berth: assembly tasks that require a robotic agent to grab and hold a large spacecraft, vehicle or module. Typically, capture is necessary before seamlessly connecting two spacecraft.
  - Heavy lift: assembly tasks that require a robotic agent to move a large spacecraft, vehicle or module. As the name implies, the robotic agent must be able to lift significant loads, usually due to the size of the spacecraft and the gravity well of the planetary body. Robotic agents may be fixed in place or may translate with the heavy load.
- Site preparation assembly task:
  - Excavation: assembly task that requires robotic agent to dig up and/or move large amounts of soil, regolith, or subsurface bedrock.
- Spacecraft support tasks:
  - System maintenance: tasks that require robotic agents to conduct spacecraft maintenance, typically mundane and/or repetitive. Maintenance may be conducted on subsystems, e.g., habitat filter system, while more complex maintenance may include servicing other robotic agents.
  - System preparation: tasks that require robotic agents to build, repair and/or conduct emergency care on spacecraft, vehicles, or other subsystems. These tasks would be the responsibility of robotic agents when the crew is unavailable (e.g., not on site) or because the task is too dangerous for the crew (e.g., nuclear power system).
- Science and assigned activity support tasks:
  - Science/sample collection: tasks that require robotic agents to collect and manipulate terrain samples. These tasks do not require the robotic agent to be in the same physical space as crew. Inherently, the robotic agent will be exposed to extreme environments.
  - Payload assistance: tasks that require mobile robotic agents to autonomously transport items for the crew's use. The agent may or not may not be in direct contact with crew.
  - Crew assistance (physical): tasks that require robotic agent to collect, hold, and handle specific items, such as tools. These tasks require the robotic agent to cooperate directly with crew. The crew and robotic agent team may be in or outside a pressurized vehicle.
  - Crew assistance (cognitive): tasks that require an autonomous agent to provide information and/or make decisions that will help crew complete and execute assigned tasks.
- Exploration tasks:
  - Scouting: tasks that requires mobile robotic agent to explore terrain of planetary body. Exploration may be on the surface, from above the surface, or sub-surface (e.g., inside caves or lava tubes). Typically, scouting does not have a scientific objective.
  - Mapping: scouting but with pre-determined science objectives. This implies the continuous use of scientific instruments and data collection.

- Sampling/analyzing: tasks that requires mobile robotic agents to collect and analyze surface or sub-surface samples. This implies the robotic agent conducting in-situ science.

Mission Planning Tasks

The fourth category of HAR tasks is Mission Planning. These HAR tasks are those that would enable mission operations [see also 14], particularly in supporting crew autonomy from ground control, and that were not explicitly identified in the previous three HAR task categories. The following HAR tasks were considered Mission Planning Tasks:

- Staging operations: Tasks that support mission objectives involving pre-deployed precursor spacecraft systems.
- Strategic planning: Tasks that support predicting and planning required to maintain long duration mission operations. Examples of strategic planning tasks include determining whether enough power is available for upcoming payload; deciding deployment of robotic assets for scouting; projecting the number of EVAs required next week, and determining maintenance schedules.
- Tactical activity scheduling: Tasks that support daily activity scheduling, which determines what the crew needs to accomplish and execute each day.
- Training: Tasks that support training needs, independent of ground control. These tasks may leverage automation or robotic assets.
- Medical Procedures: Tasks that support executing medical procedures, independent of ground control. These tasks may leverage automation or robotic assets.

Human-Automation-Robotic Interactions

Each DRM had various expectations, both explicit and implicit, with respect to the type of interactions between operators and automation or robotic agents. In order to consistently describe these assumptions, the expected interaction was reviewed and documented for each HAR task within each DRM. As a result, each task required an operator to only *monitor* the automation/robotic agent or agents, *command* the agent/s, or *both monitor and command*. Other classic descriptions of HAR interactions, e.g., teleoperation, were not included to maintain uniformity across the classification.

Human-Automation-Robotic Factors

Based on the DRM assessment, human-automation-robotic (HAR) factors were determined. These HAR factors are critical elements that will significantly influence HARI. Essentially, future HARI designers and engineers will have to contend with these factors in their design of human-system interactions, because these factors will affect the type and frequency of interactions as well as the expected overall operational human-system performance. These factors were present in all DRMs, but are more prominent depending on the particular mission phases (e.g., Earth departure vs. Planetary Surface Operations). This set of HAR factors is summarized in Table 2.

Table 2: Human-Automation-Robotic Factors Descriptions

HAR Factor	Description	Options
Communication Infrastructure	The expected communication availability between Earth and crew, as well as between crew and automation/robotic agent. It includes latency, quality, and bandwidth of communication.	The following three levels were devised according to latency: no communication issues, some communication latencies, long communication lags with limited bandwidth.
Spacesuit Environment	The expected use of a pressurized spacesuit by crew while interacting with automation/robotic agent.	Suited and unsuited were the only conditions considered.
Gravitational Environment	The expected gravity experienced by crew while interacting with automation/robotic agent.	Microgravity, partial gravity, and hyper gravity.
Colocation (Operator Proximity)	The expected proximity of the operator relative to the automation/robotic agent while the operator is commanding and/or monitoring the system.	Operator inside or close to system, operator is outside or far from system, and operator is on Earth.
System Diversity	The expected number and/or distribution of automation/robotic agents operator will interact with at any given time.	Only two options: one or many agents.

Generic Systems Classes

To compare HAR task needs across different DRMs, generic names for spacecraft and robotic systems were used.

This naming convention not only facilitated the identification of similarities across DRMs and unique needs for each mission type, but also allowed for an unbiased assessment. For instance, if a DRM mentioned using Robonaut but another mentioned robots fixing rovers, the assessment would focus on the dexterity capability, not the specific robot name.

For each of the generic systems listed below was present in at least one of the DRM categories evaluated. Few of these systems are unique to specific DRMs, while many were present in multiple DRMs. A couple, like the Crew Capsule, is described in all the DRMs.

- *Crew Capsule*: Earth ascent and Earth re-entry spacecraft vehicle. Typically, Orion or the Multipurpose Crew Vehicle (MPCV).
- *Crew Habitat Module*: Spacecraft module that is equipped for crew habitation (sleep, exercise, medical, etc.) and may enable EVA. For Deep Space Sortie, this is currently called Exploration Augmentation Module (EAM). For Deep Space Habitation, this is currently called Deep Space Habitat (DSH). For Planetary DRM, this and Crew Capsule together are currently called the Mars Transfer Vehicle (MTV).
- *Logistics Module*: Module that supports stowage, such as food, spares, and trash. Typically, it is attached to a Crew Habitat Module.
- *Small Pressurized Exploration Vehicle*: A small, pressurized vehicle that can rove on a surface or "fly." Capable of sustaining a small number of crewmembers from a few days to up to a month. Some DRMs call this vehicle the Multi-Mission Space Exploration Vehicle (MMSEV). The Lunar DRMs have both small and large pressurized exploration vehicles, where the large vehicle acts like a mobile habitat and could support crew for up to a month.
- *Unpressurized Exploration Vehicle*: A small, unpressurized vehicle that can rove on a surface with one or more crewmembers.
- *Descent/Ascent Vehicle*: A spacecraft that can conduct entry, descent, and landing on a planetary surface. Usually has an adjacent module that allows for depart from planetary surface. Mars/Planetary DRM call this vehicle DAV while the Lunar DRM calls it a Lunar Lander, which includes an Ascent Module.
- *Surface Habitat Module/Lander*: A spacecraft that supports crew habitation on a planetary surface. This is distinct from the Crew Habitat Module because the Surface Habitat is intended to operate in surface. For the long duration Mars/Planetary DRM, the Surface Habitat operates in transit, on Mars orbit, as well as the planetary surface.
- *Power Surface Asset*: An asset that provides additional power source to the mission, particularly for long duration, planetary missions. For Planetary DRM, this is a surface nuclear power plant. For Lunar DRM, this is solar and portable.
- *In-Situ Resource Unit*: An asset that uses materials from the destination and outputs useful products for crew. For Lunar DRM, options include oxygen, hydrogen, and other volatiles to supply life support, fuel-cell replenishment, and propellant. For Mars DRM this also includes production of water, and inert breathing gases (nitrogen and argon).
- *Communication Surface Asset*: An asset dedicated communication system on a planetary surface that facilitates communications to Earth. For Lunar DRM, this asset is portable. For Mars DRM this includes a high-powered communications terminal adjacent to the habitat in conjunction with an orbiting Mars network of satellites.
- *Science Instrument Station*: Science instrument assets expected to be deployed on the planetary surface.
- *Integrated Multi-System*: An integrated system of multiple surface assets connected and operated as one system.
- *Asteroid Robotic Retrieval Vehicle*: Unmanned spacecraft that travels into deep space to grab either an asteroid or a boulder off an asteroid, and returns it to a different orbit. This spacecraft is unique to the Deep Space Sortie DRM.
- *Robotic Large Manipulators*: Large robotic arms or manipulators that can carry/lift heavy items (either in place or transporting), capture other spacecraft, and dig/excavate large amounts of regolith. This robotic class may include large drilling machines.
- *Robotic Dexterous Manipulators*: Generally, smaller dexterous robotic arm/s that are on a mobile platform. They are intended to conduct maintenance, repair/emergencies, help build space assets, help crew in procedure/task execution, and maintain other robots.
- *Robotic Surface Explorers*: Mobile robots that can be on surface or "air", used for scouting (goal is not science-oriented), mapping (goal is science oriented), sampling/analyzing (using science instruments), drilling or subsurface exploration, and/or payload assistant (transporting, collecting, following).
- *Autonomous Intelligent Systems*: Augmented intelligence, decision support, or artificial intelligence that will interface with crew to help provide state information as well as decision-making. It is not meant to replace a system (i.e., crew can always interface system as "backup" interaction method). Such systems are always locally resident to crew.

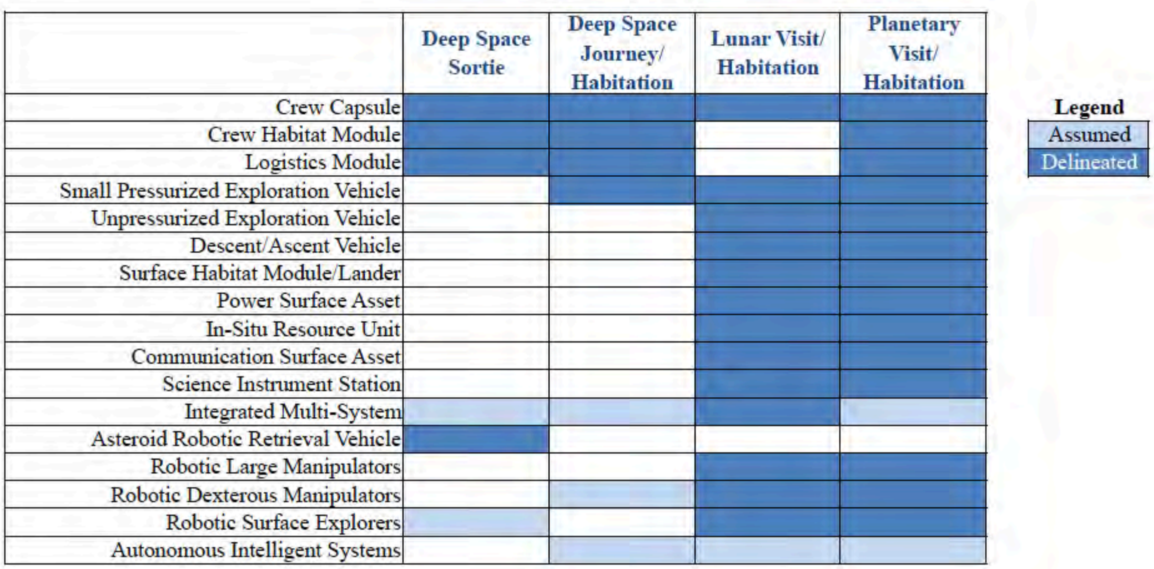

Figure 2: Design Reference Mission and Generic System Class

4. Discussion

The DRMs assessed were Deep Space Sortie, Lunar Visit/Habitation, Deep Space Journey/Habitation, and Planetary Visit/Habitation. Figure 2 shows the distribution of systems across the DRMs. This assessment shows how many more systems the surface DRMs require compared to the Deep Space DRMs. There is also only one system that is mission specific, i.e., the Asteroid Robotic Retrieval Vehicle.

Most human-automation/robot interactions identified were recognizable, however, some were assumed or extrapolated from the mission description. Figure 2 depicts the systems that are "assumed" to be present in the DRM. Since the DRMs are still in work, many of the objectives are still in flux, producing significant uncertainty as to human-automation/robot interactions that will be the required. Thus, there may be other HARI needs that do not presently exist in any documented form. Further, both presently identified and unidentified needs may change numerous times before program implementation.

Because of the breadth of the architectures involved, the cited documents do not delve to a level of detail sufficient to depict all robotic and automation systems or all of the specific HARI use cases that can be expected to arise to during a mission. Additionally, there was little information regarding the type of interaction, if crew or ground were expected to have intermittent, continuous, and/or both communications with said automation or robotic systems. Documentation of operational concepts (ConOps) would have helped better identify HARI use cases across the full spectrum of exploration tasks. Such specific identification would provide a more concrete understanding of where the mission HARI challenges reside.

In retrospect, assessing the NASA DRMs limit the types of HARI tasks that could be identified. Most of the DRM documentation focuses on systems that are part of the mission architecture, and contains was very little discussion about automation/robotic systems that could enable other mission objectives, such as science, telemedicine, or inflight training. These mission objectives will require crew to interact with additional automation/robotic systems that support these types of tasks. For example, there is minimal mention of robotic agents, such as those that could replace Apollo's Module Equipment Transporter (MET) used during lunar surface EVA. Consequently, additional resources, like the NASA Technology roadmaps and published reviews of future human-automation-robotic integration needs were leveraged in order to get a more complete assessment of HARI tasks.

Similar to the previous theme, the NASA DRM documentation does not explore or delineate the types of systems required to adequately support the crew's autonomous execution of mission tasks, i.e., autonomously from ground control. While the assessment includes generic systems that supports crew autonomy, the NASA DRMs do not specifically call out the need for these HARI systems.

A significant issue with current ISS space operations is the limited amount of time astronauts have available for the conduct of onboard research. Furthermore, a recent study suggests crew will have even less time to conduct science in future missions [17]. For the surface DRMs (Lunar and Planetary/Mars), astronauts will likely face an increase in maintenance chores based on the fact that there are so many diverse assets to manage (from habitat to new robots to rovers). While Mars DRM mentions advancements in maintenance strategies, the NASA DRMs do not elaborate on any automation/robotic systems (such as intra-vehicular robotic agents) that may offload maintenance tasks from crew. Likewise, automation and robotic systems that would increase available crew time or make it more efficient are not mentioned.

5. Future Work

The implications of this assessment will likely extend and apply to the Evolvable Mars [18] campaign as a whole. The Human Exploration Architecture Team (HAT) evaluates a wide-range of DRMs, like missions to Phobos or the Earth-Moon Lagrange Points. Most recently, the Evolvable Mars design reference mission has been of prominence. This DRM includes several destinations, each program advancing the necessary technology to reach farther into our solar system, with the goal of landing on Mars. Principally, this assessment evaluated the stepping-stone destinations delineated in Evolvable Mars, from Cislunar, Moon, an asteroid, and a deep space habitat, to Mars.

Future work will focus on further evaluating which HARI tasks and factors are emphasized within each DRM and across systems. This will be aimed as a method to identify areas of overlapping efforts, where research and advancements in one HAR area would benefit the most DRMs. Additionally, the HAR need differences between crew and ground control teams will be considered.

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BIOGRAPHY

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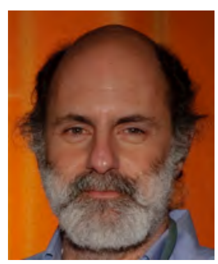

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