Task Modeling for Lunar Landing Redesignation

Zarrin K. Chua[1]
Georgia Institute of Technology, Atlanta, GA 30332

Laura M. Major[2]
Charles Stark Draper Laboratory, Boston, MA 02139

Man's return to the Moon requires advancement in landing technology to achieve safe and precise landing. The Autonomous Landing and Hazard Avoidance Technology project is developing an autonomous flight manager (AFM) to provide the capability of assisting the crew during critical landing phases, beyond the standard guidance, navigation, and control. One such phase is landing point redesignation (LPR), where the crew must select a safe landing aim point. A task model is created to analyze the functions required for the LPR task, the allocation of functions between crew and automation, and the information needed by the crew. Three bottlenecks are found in the LPR task: the inability to rapidly compare alternative aim points, the time penalty associated with changing internal mission objectives, and the hindrance of communicating such a change to the AFM. The LPR task model predicts a task execution time of 25 seconds for the best scenario, but implies design changes are necessary to improve a task execution of 5 minutes in the worst scenario. Implementation of the changes suggested in this paper will reduce crew workload and stress during lunar landing, and increase overall system risk and reliability.

Nomenclature

α = number of landing aim points displayed
Π = number of points of interest
B = primitive operator, time for mouse button press/release
H = number of hazard patterns
M_c = primitive operator, time for choosing
M_t = primitive operator, time for thinking
m = number of objective changes (early)
n = number of objective changes (late)
P = primitive operator, time to point mouse
Y = autonomous flight manager landing point redesignation processing time

I. Introduction

Man's return to the Moon requires a significant advancement in landing technology to achieve safe and precise landing. Already, efforts have been made to address this challenge, with the development of robust, adaptable autonomous systems to supplement and assist trained astronauts. These autonomous systems are particularly geared to assist astronauts in time-critical, high-risk tasks.

NASA's Exploration Technology Development Program (ETDP) is working to develop capabilities needed to return humans to the moon. One development area inside ETDP is the Autonomous Landing and Hazard Avoidance Technology (ALHAT) project, which is focused on identifying safe landing areas on the lunar surface. The ALHAT project objective is to develop an autonomous lunar landing guidance, navigation, and control (GN&C) and sensing system capable of landing safely and precisely anywhere on the Moon, where autonomous is defined as independence from any external commands.

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[1] Graduate Research Assistant, Guggenheim School of Aerospace Engineering, Georgia Institute of Technology, AIAA Student Member.

[2] Human-System Collaboration Engineer, Charles Stark Draper Laboratory, AIAA Member.

An Autonomous Flight Manager (AFM) is included in the autonomous GN&C system to provide a capability required to assist the crew in the landing phase of a lunar mission beyond the standard GN&C functions. The AFM will handle the dynamic nature of missions within the boundaries of the pre-mission planning by autonomously providing adaptive behavior for vehicle operations. A key challenge in designing the AFM and the overall ALHAT system is the allocation of tasks between the crew and the automatic system.

One of the critical functions of the AFM that must be studied is the ability to select a safe landing aim point (LAP) during the descent. This function is known as Landing Point Redesignation (LPR) [1]. The LPR task begins once the landing vehicle pitches over and first receives a view of the landing site. The landing site is viewed directly by the crew through a window and also by additional onboard sensors. A LIDAR sensor is included in the ALHAT system for effectively interrogating the surface under any lighting conditions.

A task model is created to analyze the functions required for the LPR task, the allocation of functions between crew and automation and the information needed by the crew. This task model is then used to define ALHAT system requirements based on the crew role, including time required for crew decision making. This paper presents the LPR task model and results from analysis using the model.

II. Model Description

A "top-down" modeling approach is utilized in this study, beginning with a concept-level description of the main LPR task, and then iterating on this description to determine the specific, most fundamental tasks. The nominal baseline LPR task sequence is shown in Fig. 1. As mentioned previously, this investigation is concerned with the LPR task. The LPR task begins as soon as vehicle pitches up and the terrain is viewable by the crew. However, this model examines crew behavior immediately after the terrain is within view, the LIDAR scan is complete, and the AFM determines a set of safe alternative LAPs. The crew may have a site selected from looking through the window, but the functionality to signal this intent is outside the scope of this model. Also, based on expected LIDAR and AFM processing time, the crew is unlikely to observe and decide before alternatives are calculated and presented. These system tasks are beyond the scope of this human-system interaction study and are represented by dashed line boxes in Fig. 1. Once the AFM recommendations are presented, the crew has access to the existing terrain view out the window or other means such as a camera or synthetic vision and the new information presented by the AFM, which may include highlighting of the hazards and alternative LAPs [1]. These tasks are represented by solid line boxes in Fig 1.

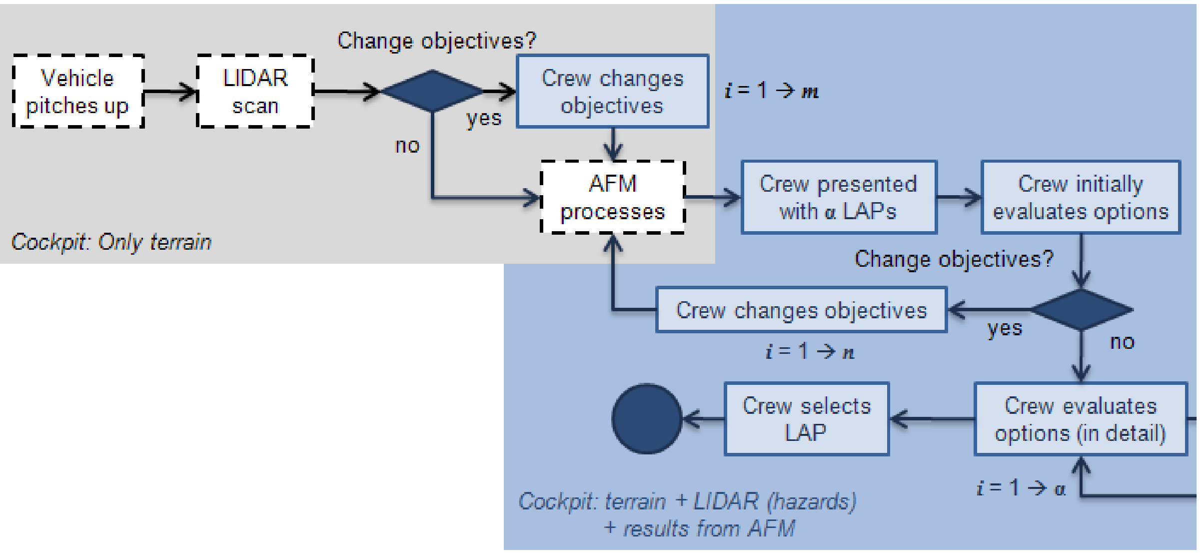

Figure 1. Landing Point Redesignation Task Flow Diagram.
Solid line boxes are within the scope of this investigation. Only the terrain is visible to the crew during the tasks in the grey shaded area. The terrain, hazard data from the LIDAR, and LAPs from the AFM are available to the crew during the blue shaded area.

Although the LPR task could theoretically occur more than once during powered descent, the focus of this investigation is the first instance of the LPR task. A similar assumption is held for the LIDAR scan – this investigation is concerned with the first LIDAR scan and the associated results. This model may assist in the determination of a secondary LIDAR scan, or the feasibility of multiple LPR opportunities. Regardless of LPR frequency, each instance of LPR is composed of five linearly executed steps, or subtasks. These subtasks and their description are:

1. **Crew presented with the LAPs**. The crew is assumed to be evaluating a window view or equivalent (i.e., synthetic vision or camera view) when the AFM presents the LIDAR results, in the form of highlighting hazardous regions within the landing site, and a number of suggested alternative LAPs. These LAPs are generated from an *a priori* weighting distribution and set tolerances of the three main objectives: to achieve the safest sites, to minimize fuel consumption, and to land close to the point(s) of interest (POI). The crew must switch their mental attention from the current activity to the LPR display.

2. Crew evaluates options (initially). After the crew has switched their mental attention to the information presented on the LPR display, they will initially acknowledge the presence of some number of hazard patterns and LAPs. Likewise, they will recall the number of POI and the location of these sites relative to the LAPs.

3a. Crew decides whether to change objectives. At this point in the process, the crew must decide whether they feel the suggested LAPs are sufficient for further evaluation or whether an objective change is needed. An objective change may be needed if something unusual is occurring, such as unexpected vehicle behavior or a larger number of hazards than expected. This model assumes that only the weighting distribution between the three main objectives can be adjusted by the crew.

3b. Crew changes objectives. If the crew decides to change the AFM LPR objectives, then they will relay this reorganization of objective priority to the AFM using operator actuators. Subtasks 3a and 3b may occur multiple times in the LPR sequence. These subtasks constitute the later opportunity to change objectives – the earlier opportunity is presented prior to AFM processing.

4. Crew evaluates options (in detail). Once the crew is satisfied with the alternative LAPs, a more thorough examination of each option commences. This examination involves comparing LAPs across measures such as terrain characteristics (slope, roughness), proximity to hazard, proximity to POI, fuel consumption requirements.

5. Crew selects landing aim point. The crew denotes their decision by using operator actuators. Completing this step concludes the LPR task.

At this level, the five defined subtasks lack the detail necessary for an LPR model. These subtasks are decomposed into linear sequences of smaller tasks, or primitive operations on a human-system interface. This decomposition requires a reference display and a task analysis schema. The reference display chosen for this investigation is the design proposed by Forest, et al. [1]. To review briefly, this display is divided into two main components – a top-down map view with hazard shading, point of interest (POI) and LAP identification. A total of three points (two alternative LAPs and the baseline) can be examined in further detail by pressing the associated identification buttons in the lower left corner. Information regarding the terrain characteristics of alternative LAPs is presented to the right of the map. Objective changes with respect to the three main objectives (safety, fuel consumption, proximity to POI) can be executed by moving sliders to a lesser or greater degree of preference.

The task analysis methodology chosen for this study is the Keystroke-Level-Model Goals, Operators, Methods, and Selection (KLM-GOMS) developed by Card et al. [2]. The KLM-GOMS methodology was selected for this study because of the ease in implementation and the appropriate set of primitive operators for the crew-LPR display interaction. The GOMS methodology breaks the main task into a set of user-defined goals; allowable actions, or operations; sequences of subgoals and operations to achieve the main goal, or methods; and selection rules, as defined and enforced by the user, in deciding on a method. The KLM variant of GOMS focuses on the operators. KLM-GOMS divides a major task into several smaller tasks until the individuals actions can be modeled by primitive operators. These primitive operators are standard keyboard operations, such as the press/release of a button and moving a mouse. KLM-GOMS also utilizes an approximation for mental activity, such as thinking/perception. However, a later study completed by Olsen and Olsen [3] noted the inadequacy of using thinking/perception for all related mental activity. As such, an approximation for the "choosing" operator was developed. Table 1 lists the primitive operators utilized in this study. One should note that these operators serve as analogies, rather than literal actions. For example, the crew is not expected to use a mouse when interacting with the LPR display. However, pointing a mouse is similar to moving a hand to a button on a display and pressing/releasing the mouse button is comparable to pressing/releasing a bezel button.

Table 1. Primitive operator execution times. *All execution times are derived by Card et al.* [2], *unless otherwise noted.*

Operator	Symbol	Execution Time, s
Mental activity		
Thinking, perception	M_t	1.2
Choosing[3]	M_c	0.62
Point mouse	P	1.15
Press/Release mouse button	B	0.2

To utilize the KLM technique, the five subtasks described previously must be further disassembled into a series of primitive operators. The estimated execution time for each operator is summed to provide an estimation of the overall task completion time. The operator interactions required to complete each of the five major subtasks are listed in Table 2. Depending on the quality of the LAPs presented, the crew may wish to make at least one objective change. Thus, as illustrated in Table 2 and Fig. 1, several of these major subtasks may occur multiple times. As such, the number of objective changes must be recorded to properly account for the total task execution time.

Table 2. Implementation of KLM-GOMS on five major subtasks.

1. Crew presented with landing aimpoints		
	Context-switching, mental activity	M_t
2. Crew evaluates options (initially)		
2a.	Mental perception of α LAPs	$\alpha\ M_t$
2b.	Mental perception of *H* hazards	$H\ M_t$
2c.	Mental perception of Π POIs	$\Pi\ M_t$
3a. Crew decides whether to change objectives		
	Mental activity	M_t
3b. Crew changes objectives		
3ba.	Perceive current and desired placement of slider	M_t
3bb.	Move slider *(approx. as pointing a computer mouse)*	*P*
3bc.	Repeat, if desired, for two more sliders min: $P + M_t$ max: $3\ (P + M_t)$	
4. Crew evaluates options (in detail)		
4a.	Select two LAPs to compare	$2M_c$
4b.	Move hand to first LAP button, press button	$P + B$
4c.	Move hand to second LAP button, press button	$P + B$
4d.	Evaluate fuel buffer for first and second LAPs, and the *a priori* point	$3\ M_t$
4e.	Evaluate the terrain for visual comparison	M_t
4f.	Evaluate safety buffer for first, second, *a priori* LAPs	$3\ M_t$
4g.	Evaluate terrain for visual comparison	M_t
4h.	Evaluate the slope buffer for first, second, *a priori* LAPs	$3\ M_t$
4i.	Evaluate the vertical buffer for first, second, *a priori* LAPs	$3\ M_t$
4j.	Repeat steps 4a – 4i until necessary. min: $2\ (P + B) + 14\ M_t + 2\ M_c$ max: $(\alpha! / (\alpha - 2)!)\ [2\ (P + B) + 14\ M_t + 2\ M_c]$	
5. Crew selects LAP		
5a.	Perceive α LAPs and *a priori* site	M_c
5b.	Move hand to selection button	*P*
5c.	Select a LAP by pressing two buttons	$2\ B$

Based on the task model, the total task execution time (cognitive and physical) is a factor of five input parameters: the AFM processing time, *Y*; the number of times the objectives are changed, *n*; the number of LAPs preseCnted by the AFM, α; the number of points of interest, Π; and the number of hazard patterns, *H*. Several key assumptions are made given the behavior of the system:

1. The LIDAR scan occurs once prior to the initial LPR task sequence and as soon as possible after vehicle pitch up. This task model focuses on the first LPR decision, acknowledging that there may be subsequent changes in the selected LAP further in the trajectory.
2. The LIDAR scan correctly identifies all hazard patterns present.
3. Hazard patterns are assessed by the crew as groups of hazards (i.e., three craters near each other are considered one hazard pattern, not three individual hazards).
4. The hazard data and LAPs are presented together after the AFM processes and recommends a set of LAP recommendations.
5. The AFM outputs the maximum number of LAPs, with no more than 5 LAPs considered.
6. The crew will considered at least one LAP other than the baseline before making a final selection.

Utilizing these assumptions and the KLM-GOMS technique, task execution times are approximated for each box in the task sequence. The time execution range is defined through Eqs. (1) and (2). The main difference between the minimum and maximum execution times is based on the number of LAPs considered by the crew, prior to selecting a final aim point. For the minimum case the crew only evaluates one alternate LAP against the baseline LAP and for the maximum time the crew evaluates all LAP options (α!/(α-2)!).

$$f = f(Y, m, n.\alpha, \Pi, H)$$

$$f_{min} = 3.55n + 2.35m + nY + (n+1)[1.2(H + \Pi + \alpha + 1)] + 19.89 \quad (1)$$

$$f_{max} = 8.25n + 7.05m + nY + (n+1)[1.2(\alpha + H + \Pi + 1)] + \frac{20.74\alpha!}{(\alpha-2)!} + 4.57 \quad (2)$$

where *Y* is the AFM processing time, *m, n* are the number of objective changes (during initial presentation and after detailed evaluation, respectively), α is the number of alternative LAPs, Π is the number of points of interest, and *H* is the number of hazard patterns. For a scenario with a well defined number of hazards and points of interest, the maximum and minimum time to complete the LPR task can be approximated.

III. Model Results and Discussion

Table 3. ANOVA inputs.

Input	Minimum	Maximum
Y	0.75 s	
α	1	5
n	0	3
H	1	4
Π	1	3
m	0	1

A full-factorial analysis is performed over a range of inputs, as listed in Table 3. The resulting $5 \times 4 \times 4 \times 3 \times 2$ design of experiments produces 480 unique scenarios. An ANalysis Of VAriance (ANOVA) is used to determine the significance of the independent variables. As can be expected, the minimum time was achieved in the case of 1 landing aim point considered (i.e., baseline point and another alternative), no objective changes, and the safest terrain (one hazard pattern, one point of interest). This time of 24.69 seconds, was used to normalize the time of the other scenarios. The maximum time occurs in the case of 5 LAPs considered, several objective changes (one early, three later), and rough terrain (four hazard patterns, three points of interest). This time recorded is approximately 12.5 times more than the minimum, with a time of approximately 5 minutes. Fig. 3 illustrates a slice of the expected range of execution time. This figure represents the result of variances in number of objective changes in the later case, n, and number of LAPs, α, for four hazard patterns and one POI.

As illustrated in Fig. 3, the number of objective changes (in the later case, n) and the number of LAP options presented to the crew (α) has a significant impact on the execution time. The minimum execution time is most influenced by n ($p_{n(\min)}$=0), contributing $Y + 1.25(H + \Pi + \alpha + 1) + 3.55$ seconds with every new objective change. Conversely, an earlier change, m, contributes only 2.35 seconds. Surprisingly, a later objective change has a lesser effect on the maximum execution time. Although every later objective change adds seconds to the maximum $Y + 1.25(H + \Pi + \alpha + 1) + 8.25$ time, there is a more dominant contributor. This contributor is α ($p_{\alpha(\max)}$=0), and dominates with each α combination adding 20.74 seconds to the final time. This costly time penalty is because the number of LAPs potentially considered by the crew is dependent on the number of LAPs presented and the limitations of the reference display. An assumption is made that all α LAPs are compared to each other and the baseline. This one-to-one comparison technique elongates the decision time. Additional analysis reveals that the number of POIs presented to the crew nor the number of hazards have a significant effect on either the minimum or maximum execution time ($p_{H(\min)}$=0, $p_{H(\max)}$=0, min and max respectively).

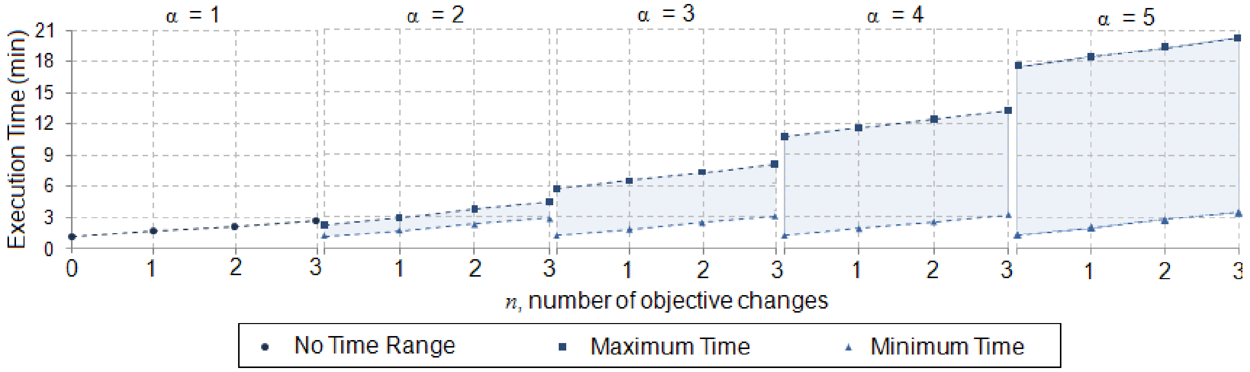

Figure 3. Trends in task execution time. *The execution time is normalized to a most minimum time of approximately 25 seconds. The shaded area is the range of time. These cases are for four hazard patterns (H = 4), one point of interest (Π = 1). Only the later opportunity for objective changes is considered in this case.*

The results presented in Fig. 3 highlight the need for changes to reduce crew workload and improve the LPR task. This analysis illuminates several task bottlenecks. First, there needs to be a reduction in the number of LAPs that the crew should consider, or a redesign of the LPR display to quickly provide LAP information. As illustrated in Fig. 3, each additional LAP effectively adds another minute to the (potential) maximum time spent completing the LPR task. The reference display allows the operator to select two alternative LAPs (out of α presented) to compare with the baseline. After choosing these sites, the operator must compare terrain characteristics such as fuel cost, slope, roughness, and proximity to hazard, to the photorealistic landing map (see Table 2 for modeling). If a feasible site is not found, the operator must select another two sites for comparison and repeat this process. To thoroughly investigate all landing site alternatives, the operator must examine every combination of LAPs, including those sites previously examined.

This second bottleneck concerns the number of objective changes and when these changes occur. As mentioned in the previous section, there are two opportunities for objective changes – as soon as the LIDAR scan is occurring and after initial evaluation of the LIDAR information by the AFM to determine a safe set of LAPs. The first opportunity for an objective change may be the result of out-the-window terrain viewing. For example, the operator may view the terrain as particularly hazardous, perhaps more so than expected, and opt for safer sites that are farther away from hazards. This change would occur before any extensive review of the LAPs is initiated. The second objective change may be a reaction to AFM/LIDAR information. The operator may not find the initial alternative LAPs suitable, and adjust the safety, fuel consumption, and POI weighting to better match the operator's internal objectives or the situation. Once this change is made, the AFM produces new alternative LAPs based on the new objective (thus incurring a processing time penalty) and the new LAPs are once again, initially evaluated for crew acceptability. This process is repeated until the crew receives suitable LAPs for more detailed evaluation. As expected, a later objective change is much more time costly, as several steps repeated.

The third bottleneck is minor compared to the first and second bottlenecks, but warrants further investigation to ameliorate the time penalty. The current reference display requires that the crew adjust three sliders to set a specific distribution of preference between the three main driving factors. These sliders are adjusted between 'less' (-) and 'more' (+). Although only one slider movement is necessary for an objective change, the crew could adjust each slider bar until a precise weighting distribution is achieved. This task is further complicated as the only feedback provided to the crew is a visual distribution of the weighting, rather than a numerical printout. While this adjustment is a relatively quick maneuver, repetition can cause a bottleneck of the LPR task.

The bottlenecks identified (detailed evaluation, objective changes, and the physical act of changing objectives) are a problem of interest for LPR task completion. In some cases, up to 97%, 61%, and 51% of the execution time, respectively, was spent on these steps. The significant difference between the minimum and maximum execution times, especially in the higher α cases suggests that there is need for improvement of the LPR task. The maximum and minimum times are not error estimations in the traditional sense, but could be considered as such, for design purposes. At the current moment, the worst case scenario of landing in an area with four hazard patterns with three points of interest (assuming that five LAPs are presented) results in an expected LPR task execution of about 97 seconds to a little over 5 minutes. This time estimation should come with the caveat, however, that there is unlikely to be 5 minutes available during this final mission segment. Apollo missions had 120 seconds or less.

The time requirements for crew decision making poses a challenge for mission and trajectory planners alike. The LPR model results imply a need for an onboard decision aid to more rapidly compare multiple LAPs with the baseline recommendation. This decision aid could prompt a redesign of the LPR display, to better convey critical information and allow for improved crew-system communication. These changes would alleviate the workload associated with comparing the alternative LAPs, which was the cause of the first bottleneck. Likewise, these changes may also eliminate the need for multiple objective changes, the second bottleneck identified with the LPR model. Quickly identifying and conveying satisfactory sites and the associated information would reduce dissatisfaction with the alternatives and thus reduce objective changes. This bottleneck could also be avoided with strict operating policies. That is, if the crew is trained to not change objectives more than a certain number of times. Lastly, the third bottleneck, minor in comparison to the first two, can be alleviated with a better mechanism to pass information to and from the crew.

IV. Conclusion

The LPR sequence is a mission critical and time-sensitive task that carries considerable consequences. The task model presented in this paper examines the events after the LIDAR scan and utilizes the reference display as proposed by Forest, et al. [1]. This task model also estimates the minimum and maximum time range of performance for LPR task execution. Of all potential scenarios, the minimum time needed for LPR is approximately 25 seconds. Conversely, the worst case scenario could require 5 minutes to complete. By applying this model in a variety of scenarios, three bottlenecks are identified. These bottlenecks highlight information needs, automation needs, display design constraints, and restrictions on the mission design. The results suggest the alleviation of the bottlenecks identified in this research is necessary. Implementation of the changes suggested in this paper will reduce crew workload and stress during lunar landing, and increase overall system risk and reliability.

In general, the approach of developing a task model of significant mission tasks can be applied to more clearly define the set of functions that need to be performed and the allocation of functions between humans and automation. Such a task model is useful in performing first order analysis needed to define timing requirements and information requirements and identify bottlenecks in crew decision making that may benefit from additional automation support.

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