Flight and In-Water Experiments of Autonomy and Human Interface Technologies with Multiple Unmanned Systems

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ABSTRACT

This paper describes operator, flight, and in-water experiments with autonomy and human interface technologies for management of multiple unmanned air, sea surface, and undersea vehicles. The vehicles were managed by a single operator based on high-level mission objectives, constraints, risks, and priorities. The scenarios explored contingencies and changes in tasking that required both operator-driven and fully autonomous dynamic replanning. Live asset and laboratory experiments were performed using six to seven naval operators with different backgrounds including air and sea vehicle operators and mission commanders. The test vehicles for the live experiments were two Kestrel fixed-wing Unmanned Air Vehicles, 1 small hand-launched UAV, a high-speed Unmanned Surface Vehicle (USV), and the Autonomous Maritime Navigation (AMN) USV. The AMN USV was also used as a surrogate for an Unmanned Undersea Vehicle (UUV) performing a surface reconnaissance and surveillance mission. Additional vehicles were simulated including multiple UUVs involved in search tasks. The vehicles had different levels of on-board autonomy. Some were sent high-level mission tasking only, and others were sent detailed plans. Standardization Agreement (STANAG) 4586 Command and Control and Common Route Definition (CRD) format was used to communicate with the vehicle auto-pilots. Data was collected on a range of system and human/system performance metrics. In addition to discussing results, this paper will provide some lessons learned.

INTRODUCTION

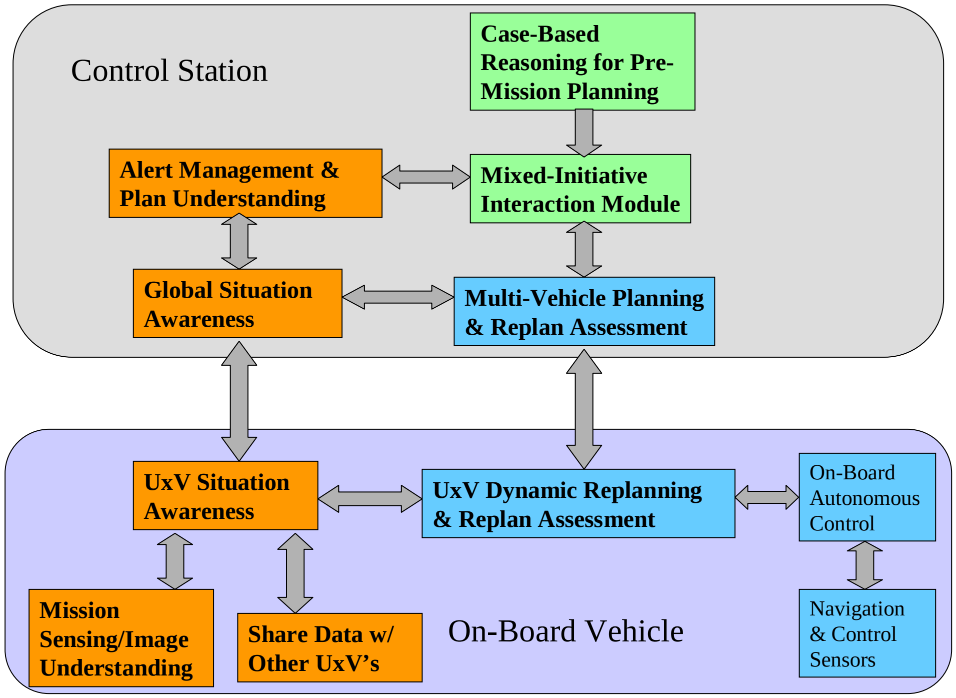
In 2002, the Office of Naval Research began a program to develop and demonstrate intelligent autonomy technologies for mission management of five to ten unmanned air, sea, and undersea systems on littoral surveillance and reconnaissance missions.[1-2] There were three primary goals of the program. The first was to reduce the need for human intervention in unmanned system operations by enabling highly automated re-tasking and fully autonomous dynamic replanning to deal with changes in tasking, constraints, the mission situation, or the environment. An important aspect of this was ensuring robust operations in environments with highly limited communications, particularly for autonomous undersea vehicles that might communicate with an operator only a few times a day. The second goal was to investigate the extent to which it is possible to develop a common human interface for a family of highly heterogeneous unmanned systems. A challenging aspect of this was the need to provide acceptable operator situation awareness and workload even for operators with different backgrounds that were not expert in each of the systems being controlled. This was particularly difficult as the vehicles were significantly different both physically and with regards to their level of on-board autonomous control. The final goal was to reduce the high workload associated with managing multiple heterogeneous unmanned systems. Some high workload drivers that were of interest included planning and replanning, responding to system contingencies, coordinating vehicles on collaborative tasks, managing risks, and optimizing plans around restricted areas, hazard areas, and the routes of other vehicles. Also of concern was the workload involved with maintaining operator situation awareness while utilizing large amounts of data from many different sources.

As the program progressed, much attention was directed to several other areas as well. First of all, work on how to design user interfaces gradually transformed to address broader concerns about how best to design all of the components in a mixed-initiative autonomous system to support the role of the user, and how particular design choices impact on human/system performance. Examples of this include investigating the value of variable levels of autonomy, the effect of different types of unmanned system and mission heterogeneity, and how many vehicles a single operator could effectively manage in different circumstances. A second area of concern was understanding the limits of modularity in a common architecture used to integrate autonomy components from different industry, government, and academic organizations. As the level of integration and realism increased in phased experiments, problems were seen due to undesirable dynamic interactions between the different decision-making and control loops. Finally, there were some significant challenges in determining what metrics and test procedures would be most useful for evaluating these types of systems. Each experiment provided additional insight into how best to apply these approaches to assess the individual technologies and the overall human/machine system.[3]

This paper will provide a brief overview of the intelligent autonomy technologies developed and utilized under the program, and then describe the final experiments. This included three laboratory operator experiments with seven to eight unmanned systems, two in-water experiments with an Unmanned Sea Surface Vehicle, and a major live asset demonstration with a mix of four types of unmanned air and sea vehicles at the Wallops Island range. For information on prior experiments, see refs 1-2. Finally, results, lessons learned, and conclusions will be discussed.

1. SYSTEM ARCHITECTURE AND COMPONENTS

To increase the opportunities for technological innovation, the program was designed around a publish/subscribe architecture so that different organization's autonomy components could be integrated together in a relatively modular way. Data interfaces were designed using common XML schema, and Standardization Agreement (STANAG) 4586 Command and Control and Command Route Definition (CRD) format was used to communicate with the auto-pilots of live assets in field experiments. For more details on the integration challenges associated with the program, see ref. 4. Fig. 1 shows the overall system functional architecture. The operator interacts with the system using a



mixed-initiative interface. This interface allows the operator to specify missions at a high-level based on high-level objectives, constraints, priorities, and risk tolerances. Table 1 shows an example of some of the types of tasking the operator can specify. In addition, the operator can specify the level of autonomy for responding to various contingencies. Several different options were looked at under the

Region Types (may be vehicle specific or limited in time of effectivity)	Objectives	Risk Mitigation (can be applied to specific vehicles & mission segments)	Optimization Criteria	Constraints not associated with geographic regions
-Search Area -Avoidance Zone -Risk Zone (mission or safety risk) -No Surfacing Zone -No Comms Zone -Operating Envelope -Secondary Coverage area (collect data if does not interfere w/ primary mission)	-Search (whole area, roads, coastline, particular mobile or stationary target) -Collect imagery or ESM data -Persistent monitoring of choke point/target -Track -Go to waypoint -Loiter -Communicate	-Vehicle loss due to threat or collision -Vehicle detection -Vehicle loss due to fuel/energy -Sensor collection failure due to weather, lighting, etc.	Meet all mission objectives & constraints while optimizing: -Risk -Timing (total mission time or time to complete higher criticality tasks) -Maintaining LOS with cooperating entities -Maximize coverage of secondary areas	-Max time between Communication -Task Precedence & hard time constraints -Max Depth/Altitude & Obstacle Distance -Minimum reserve energy/fuel -Vehicle/Task Assignments by Operator (if desired)

Table 1 Examples of Operator Mission Tasking

course of the program to improve the operator's ability to rapidly task and re-task the system and maintain situation awareness. First, a Case-Based Reasoning (CBR) system was examined as a way to simplify specification of missions.[5] This utilizes past mission plans to create templates for new missions. Second, a number of different approaches were examined to support operator understanding of unmanned system plans, decisions, and mission status.[6-9] To accomplish this, cognitive work and task analyses were done to better map the operator's information requirements. The resulting designs included new ways of conveying health, status, and task information. This included improved task allocation and timeline displays, better grouping of data on the displays to draw the operators attention to important information, and better integration of spatial and temporal data.

After tasking is specified with the user interface, a multi-vehicle planning component allocates tasks to platforms and determines a schedule of mission objectives and constraints that can be sent to individual vehicle route and payload planners.[10-12] In some cases, this detailed planner was on-board the control station, and detailed plans would then be sent out to the vehicle auto-pilot. In other cases, as shown in Fig. 1, the vehicles would have an on-board dynamic replanning and mission assessment capability, and only high-level mission objectives need be sent out from the control station to the vehicle. Further, after plans were developed to meet all primary mission objectives and constraints, the system could modify plans to maximize sensor coverage over areas of interest. This used a receding horizon approach, and took into account hard spatial and temporal constraints to avoid impacting the primary mission plan and also addressed deconfliction of flight paths and coupling between vehicle flight path and sensor field of view.[13] Another approach towards multi-vehicle task allocation examined fully distributed collaboration with no centralized task allocation. In this case, when communications are available, platforms share information on available, completed, and assigned tasks, and task allocation is then determined by each platform in a decentralized manner that is robust to limited communications. This latter capability was not integrated into the broader architecture of Fig. 1, but was demonstrated in several flight experiments on its own.[14-15]

To deal with contingencies, the planners also have a replan assessment capability that can determine the impact of contingencies on the ability of a vehicle or team to carry out their current mission plan. This includes events such as the loss of a vehicle, system degradation, pop-up threats, changes in constraints, and weather. If a plan is determined to no longer be valid, the system can generate new plans either fully autonomously or with operator interaction, depending on the level of autonomy and the current communications status. There were also different events that could trigger autonomous decisions, such as if a target of interest was detected. To support this, the program developed a maritime image understanding capability for onboard USV and AUV platforms. This included the ability to classify surface boats into broad types and to identify a particular known ship from imagery. The approach towards the latter used a Scale Invariant Feature Transformation (SIFT) that automatically determined features that could be used to identify a particular ship of interest.[16] For live demonstrations, the system also had access to tracks from external sources such as the Automatic Identification System (AIS) and the Global Command and Control System - Maritime (GCCS-M).

2. LABORATORY HUMAN FACTORS EVALUATIONS

There were three main laboratory operator evaluations in the fall of 2007 as summarized in table 2. Each evaluation had six to seven active duty and retired participants from Littoral Combat Ship (LCS) Mine Warfare Detachments One and Two, NAVAIR, and VC-6 Detachment. Participants were split roughly evenly between unmanned air and undersea system operators, and included both officers and enlisted. The amount of experience and training with unmanned systems by the participants varied from months to years. The process used in the operator evaluations is described in refs 3 and 17. The evaluations provided an opportunity for feedback via a debrief and questionnaires, and data was collected on specific human/system performance metrics. The primary metrics used were Situation

Awareness probes with the Situation Awareness Global Assessment Technique (SAGAT), workload measurements using a modified version of the Cooper-Harper Rating (CHR) and the NASA Task Load Index (TLX), task and reaction times, mental model matching, system usability scales, and user satisfaction ratings.[17] In one of the evaluations, trust scales were also utilized.

The first evaluation listed in table 2 looked at operator management of an integrated system with all of the components shown in Fig. 1 in order to manage four UAVs and two UUVs . The mission tasking

Table 2 – Fall 2007 Laboratory Human Factors Evaluations

Demo/Performer	Platforms	Payloads	IA Components	Summary
Operator Eval (usability, automation levels,system /mental model compatibility) -Lockheed Martin -Georgia Tech. -Univ of Penn. -NAVAIR	Simulated -2 Penetrating UAS -1 HALE UAS -1 Tactical UAS -2 UUV's	Simulated sensors using Joint Integrated Mission Model (JIMM) Scenario -EO/IR -SAR -Comms Link -Weapons	-Operator Interface & Alert Management, & Case-Based Reasoning -Multi-Vehicle Planning, & Secondary Task Optimization -UxV On-Board Replanning & Lower-level GNC -SA & Replan Assessment	Surveillance of multiple ships, warehouse, & truck convoy in littoral area. No fly & no communications zones. Replan following changes in weather, sensor failures, and the addition of new restricted zones.
Operator Eval (Mission Heterogeneity) -CRA -MIT -Draper Lab	Simulated -4-8 UUV's -1 HALE UAV	Simulated EO/IR Sensor Mast with automatic target cueing Mine Detection Comms Link	-Mixed-Initiative Interface with Plan Understanding & Assessment -Situation Awareness on control station & on-board vehicles Multi-Vehicle & On-board Planning- Lower level Autonomous Control	3 scenarios examined 4 UUV ISR Mission to search for target of interest in 4 possible areas 8 UUV MCM mission with areas to search 8 UUV's for both ISR and MCM operations
Operator Eval (Grouping data on the Display) -Aptima -Univ. of Iowa Lockheed-Martin	Simulated -2 Penetrating ISR UAS -2 Tactical UAS -1 HALE UAS - 2 UUV	Simulated -EO/IR -SAR -Mine Detection	-Operator Interface & Alert Management, & new display layers -Multi-Vehicle Planning -UxV On-Board Replanning & Lower-level GNC -SA & Replan Assessment	Search for maintain surveillance of ship of interest. Search for mines in suspected areas.

had seven to nine major mission objectives, and operators rated the scenario complexity as moderate. Overall, operator response was positive, and the great variation in prior unmanned systems experience by the participants did not appear to substantially impact the operator's ability to accomplish the tasks. Nonetheless, operator workload was slightly higher than desirable. Average CHR was about 4.4 compared to a desired score of less than four. This indicates that moderate workload was required to carry out the tasking and there were some minor to moderate deficiencies that warrant improvement. The Situation Awareness probes also indicated some need for improvement as operators were sometimes losing SA of mission execution while they were involved in mission planning activities. Operators thought that the system could supply the information they needed much of the time, but it could sometimes be difficult to find. However, there were significant issues identified with understanding alerts, failures, and what the autonomy was doing and why. This is a problem that was noted in previous evaluations with managing three to four vehicles, but it seemed to be even more significant in this case with six platforms to manage. Some other important areas identified by the operators for potential improvements included the need for checklists that would guide the user through each task, easier ways of inputting some tasking, and safeguards to prevent against errors.

The other two laboratory user evaluations focused on interface improvements that were developed after completing a Cognitive Task Analysis and Cognitive Work Analysis respectively. The first of these also focused on to what extent issues of mission heterogeneity would impact on human system performance.[6] It examined this by having the operators execute three different scenarios. The first scenario was a simple ISR mission with 4 UUV's. The second scenario was a more challenging Mine Counter-Measures (MCM) mission with 8 UUV's. The final one was a heterogeneous scenario with 4 UUV's performing the simpler ISR tasking and the other 4 performing the more difficult MCM tasking. Results showed that operators were capable of managing even eight vehicles in all of these scenarios with acceptable workload. Interestingly, workload was highest and situation awareness lowest for the heterogeneous 4-ISR/4-MCM scenario despite the fact that it was the last scenario done and operators had the greatest familiarity with the system by that point. For example, average CHR ratings of workload were about 3 for the first two scenarios, which are very good scores that indicate minimal effort was required for desired performance. In contrast, the heterogeneous scenario had an average CHR of about 4, which is borderline good.

The final operator evaluation looked at a seven vehicle scenario, and focused on determining the impact of approaches towards grouping multi-vehicle data together to reduce workload while also allowing access to lower level information for diagnosis and exploration.[8] These display concepts were implemented as information layers overlaid on top of the baseline operator displays that were used in the first evaluation described. The goal was to provide the operator a better understanding of what the autonomous system was doing and why. This led to some improvements in usability and in trust. In particular, the results indicated improvements in operator trust in the autonomous system replanning strategy, the overall system, the straightforwardness of automation, and understanding the intent of the automation despite the fact that the underlying automation had not changed. A number of the display concepts were reported as being valuable by the operators including improved timeline information better integrated with the map display, improved integrated threat displays and representations of time on task, and the use of a task matrix for evaluating plans.

3. LIVE ASSET EXPERIMENTS

There were three live asset demonstrations that were conducted in fall 2007 as shown in Table 3. The first two demonstrations focused on high-level tasking, re-tasking, and dynamic replanning using the AMN USV with on-board dynamic replanning. The first demonstration at NASA, Wallops focused on a shoreline search scenario including the use of automated maritime image understanding within the control loop. The SIFT algorithms were able to correctly identify the patrol boat as a particular

Table 3 – Fall 2007 Live Asset Demonstrations

Demo/Performer	Platforms	Payloads	IA Components	Summary
Littoral Search Demo at NASA, Wallops -Draper Lab -Charles River Analytics/MIT -GDRS -NUWC	-1 AMN USV (surrogate for UUV on ISR surface mission) -UAV -Simulated UUV -	EO with on-board image understanding Tracks from AIS & GCCS-M (Track fusion using ASCM) -Simulated ESM -GPS & Compass for USV Navigation -STANAG 4586 interface over UDP/IP to USV Auto-pilot	-Mixed-Initiative Interface w/ risk management -Situation Awareness w/ weather data assessment -Multi-Vehicle & On-board UUV Planning -Lower level MRD UUV mission control software -Track management & image understanding	EO Search, ESM Search, Sentry, & Comm Relay tasks. ID known ship (Guardian Patrol Boat) Optionally receive tasking from Lockheed Multi-Vehicle Planner. Exclusion and no surfacing zones. Risk mitigation & assessment to detection-risk, high traffic regions, and moving tracks.
Expeditionary Command & Control (hand-off control from ship to shore) -Draper Lab -Charles River Analytics/MIT -NSWC	-AMN USV -Stiletto (Ship-based control station)	-EO -Simulated ESM -GPS & Compass for USV Navigation -STANAG 4586 interface over UDP/IP to USV Auto-pilot	-Mixed-Initiative Interface -On-Board & Control Station Situation Awareness -Distributed USV planning & tasking - On-board USV Dynamic Replanning	ESM and EO searches of shoreline. 11m RHIB acting as threat Handover control from ship-based control station to shore-based control station. Static & moving exclusion zones.
Flight/In-water demo at NASA, Wallops -Lockheed-Martin -Univ. of Penn. -Georgia Tech. -NAVAIR	-2 Kestrel UAV's -Micropilot small UAV -AMN USV (surrogate for UUV on ISR surface mission) -HSMST USV -Simulated UUV's	EO with on-board image understanding Tracks from AIS -Simulated ESM, SAR, and Weapons -STANAG 4586 interface over to various auto-pilots	-Operator Interface & Alert Management, & Case-Based Reasoning -Multi-Vehicle Planning, & Secondary Task Optimization -UxV On-Board Replanning & Lower-level GNC -SA & Replan Assessment	Monitor shipping activity, search, and strike tasks in coastal area. Moving & time-critical targets. Guardian Patrol Boat as Target of Interest. Thomas Reed as possible patrol boat. Contingencies requiring dynamic replanning included change in tasking, threats, weather, and failures.

target of interest when it was in the image frame and did not have any false alarms. However, getting the target boat in the frame of the video provide to be more of a challenge than expected, particularly due to boat roll on the days of testing. The second in-water demonstration was done as part of a larger expeditionary experiment. This showed the ability to hand-off control of the USV system from a ship-based control station to a shore-based one. Both locations had a Mixed-Initiative Interface and were able to provide different sets of high-level tasking to the USV.

The final major demonstration looked at a collaborative mission with four different types of air and sea vehicles at the NASA, Wallops range. For more details on the challenges involved with carrying out this demo, see ref. 4. Operators were given new tasking and information at approximately 30, 45, and 50 minutes into the scenario that required some degree of replanning. The results showed that human performance metrics and operator feedback tracked fairly well with the laboratory evaluations. Average operator workload was a CHR 3.5, which is considered good. Operator comments and usability scores were also not unlike the laboratory results.

4. DISCUSSION OF RESULTS

In each experiment, missions were successfully executed on the basis of high level mission objectives, priorities, risks, and constraints. Further, users reported that the variable autonomy and autonomous replanning was helpful and could provide considerable benefit in an operational environment. However, there were a number of limitations that were encountered with the system. First, the system lacked sufficient protections to prevent operators from making errors in specifying tasking. Operators also felt that the system could have been improved with a checklist function or other way to assist the operators in following the proper sequence of actions. Second, there was not sufficient help to assist the operator or autonomy in relaxing constraints or tasks when the mission specification was not feasible to carry out with the available assets. There were also problems with the system replanning too rapidly or with too little explanation to the user. A more sophisticated approach towards determining when replanning is really necessary and explaining the rationale for replans would have been valuable. Another serious problem encountered was that complex plans might no longer be effective by the time they were approved and sent out to all assets. This is particularly a problem due to the use of vehicles such as undersea vehicles that may be outside of communications for long periods of time and whose current status is uncertain. It is important that plans be robust to what the situation may be by the time the plan is approved and communicated out to all assets.

Results from the experiments were positive in supporting the ability of a single user to plan and execute a mission for multiple, highly heterogeneous systems using a common mixed-initiative interface. Measures of workload, situation awareness, usability, and user comments supported this. The results also supported the ability of a range of operators with different skills, backgrounds and training to utilize the system. Users reported that it was relatively easy to get started with the system even with limited training. However, they also indicated the need for improvements to provide the operator more flexibility to shape the behaviors of the autonomous components and improve situation awareness. Many of the ways that operators influence system execution are through hard constraints. Operators also indicated in interest in being able to positively influence the system to prefer some types of behaviors or tactics over others. Finally, one of the biggest weaknesses found was in the area of alerts and interruption management. Users reported missing alerts, and wanted more understanding of what was causing failures and why the automation was making the decisions it was making.

The experiments provided some interesting data on how many vehicles a single operator could effectively manage in different circumstances. It was thought that seven to eight heterogeneous vehicles could be sufficient to overload the operator and create serious problems. However, that did not happen in any of the scenarios. There are several reasons why operators may have been able to handle so many vehicles simultaneously. First, requiring major replans at fifteen minutes intervals seemed to be getting close to the limit of what was feasible for the operator and system to handle. A more dynamic environment with a faster tempo might have caused more serious problems. Second, the contingencies were fairly easy to diagnose. Workload would likely have been higher if contingencies had required more complex analysis. Third, scenario complexity was considered moderate by the operators. Greater complexity might create more difficulties when managing that number of vehicles. Finally, there was limited workload involved with sensor management and data interpretation. This would be a major workload factor in other types of scenarios.

An additional important result was that human interface approaches developed after performing some type of a cognitive task or work analysis of the warfare area generally were rated more highly by users than designs that did not incorporate this type of human factors analysis up front. This is relevant not only to the user interface design, but can also help allocate functionality between the human and the automation, support the development of appropriate levels of autonomy, and ensure the user's information requirements can be met. The latter can be critical to ensuring the operator can be provided with the feedback necessary for situation awareness and trust in the system. Interestingly, examination of operator trust seemed to indicate that predictability can be a more important factor than capability or accuracy when it comes to achieving trust in the system.

5. CONCLUSIONS

The operator and live asset experiments demonstrated the system's ability to reduce both operator workload and the need for human intervention through a combination of autonomous planning, control, and human interface technologies. Multi-platform missions were successfully executed on the basis of high level objectives, priorities, risks, and constraints rather than lower-level vehicle control. Fully autonomous dynamic replanning was successful within certain limitations, and operators with a range of different backgrounds and experience were able to manage highly heterogeneous air and sea systems through a common mixed-initiative interface. Nonetheless, some important limitations of the technologies were encountered, and many of these involved situations where there was a need for close collaboration between the user and the autonomy. Thus, one of the major lessons learned from this program is that it is critical to understand the role of the user in the development of all of the components in an autonomous system and not just the user interface. Another major lesson learned is that it is possible to create useful autonomous behavior for multiple heterogeneous systems using the current state of the art of optimization and planning algorithms if the problems are formulated correctly. Earlier on in the program, it was assumed that some significant technological advances would be required to solve very complex task allocation, scheduling, and route and payload planning problems. Instead, the predominant technique that was used was to decompose and constrain the problem to make it solvable with current state of the art techniques, and to make use of human tactical understanding and judgment to the extent possible to improve on autonomous planning and execution. This, however, can make the approaches more tailored towards specific missions, environments, and sets of platforms. As a result, it is not wholly clear how well the technologies and system design described in this paper could be applied to other domains or scaled to larger, more complex problems.

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