A Human-on-the-Loop Autonomy Architecture for Resident-AUV Undersea Support Infrastructure

Pedro Andrés Forero, LorRaine Duffy, and Eric Hendricks

Naval Information Warfare Center Pacific
San Diego, California 92152, USA
Emails: {pedro.a.forero; lorraine.duffy; eric.hendricks}@navy.mil

***Abstract*—The use of Resident Autonomous Underwater Vehicles (R-AUVs) is a necessary step towards increasing the safety and reliability of undersea infrastructure ranging from communication cables to oil pipelines and undersea observatories. Undersea Support Infrastructure (USI) for R-AUVs will provide docking, energy and communication services. Furthermore, it will be able to autonomously interact with R-AUVs, while enabling remote human operators to oversee, and in some cases direct, the R-AUVs and USI operations. This is particularly critical in situations where assured communications between operators and the USI are not guaranteed. This paper proposes an autonomy architecture for USIs that pursues a vertical and horizontal separation-of-concerns architecture-design approach and builds on well-documented autonomy and autonomic system design principles. Horizontal separation allows for configuration strategies and behavior policies to be defined, selected, executed and monitored by loosely coupled planning modules acting as arbitrators. Vertical separation enables decision making components to be grouped according to the timeliness of the decisions they must make. Our autonomy architecture features a dual, local and global, planning layer that provides an interface for the operator to interact with the USI, enables human-on-the-loop autonomy, and supports autonomous operations in situations where the communications between the operator and the USI are unreliable and intermittent. A use case for this architecture in the context of future at-sea inspection, maintenance, and repair services for the oil and gas industry is discussed.**

Keywords–Autonomy architecture; resident autonomous underwater vehicles; inspection, maintenance and repair; human-machine interaction.

I. INTRODUCTION

Ocean exploration and monitoring activities for both civilian and military applications are increasingly integrating sensor payloads with underwater vehicles to satisfy their need for deeper and persistent reach [17], [21], [24]. Commercially-available Autonomous Underwater Vehicle (AUV) technologies can routinely reach depths of up to 6,000 meters – the average ocean-depth has recently been estimated at 3,682 meters [6] – and conduct unattended operations for several days [21]. Furnished with advanced sensors and actuators, underwater vehicles are able to perform undersea data collection and actuation in environments previously considered too risky, costly or inaccessible for manned operations. Although challenged by the harsh environmental conditions and the intense pressure characteristic of the deeper parts of the ocean, advances in AUV design and material science will continue extending the AUVs' ability to operate deeper and longer underwater.

Despite the success of AUVs, long-term AUV deployments continue to require frequent human intervention. For instance, AUV batteries must be periodically recharged or replaced by a human operator. Coupled with the low-bandwidth acoustic channels and high-energy cost-per-bit associated with underwater acoustic communications [7], and the increasing demand for larger volumes of undersea data, the availability of limited data storage and processing capabilities onboard an AUV imposes a requirement for periodic data downloads. Not only is human intervention costly and risky, but it is also a limiting factor for the duration and operational rhythm of AUV operations. Despite these challenges, AUV capabilities in the areas of navigation, actuation, maneuverability and artificial intelligence have continued to mature [17], [21]. Indeed, the new generation of underwater vehicles combines attributes of AUVs and Remotely Operated Vehicles (ROVs) that facilitate actuation using anthropomorphic capabilities [1], [23].

Continual inspection, maintenance and repair (IMR) services for undersea infrastructure is a nascent application area for AUVs that considers the use of *Resident* AUVs (R-AUVs) [11], [15], [20]. IMR activities have been traditionally conducted by ROVs tethered via an umbilical cable, which provides power and communications, to a manned vessel or surface platform from where a human operator controls them. Pre-deployed support infrastructure will enable R-AUVs to remain unattended in proximity of the undersea infrastructure they intend to support [8], [10]. Not surprisingly, R-AUVs are expected to significantly reduce deployment and maintenance costs associated with AUV-transit in and deployment from a manned vessel, which for a typical IMR campaign can be as high as US $120,000 per day [11]. While *on-call*, R-AUVs will be able to respond quickly to IMR requests, provide support in spite of surface weather conditions, and accommodate operations in ice-covered seas. AUV docking platforms stationed several meters below the sea surface can protect R-AUVs from storms and maritime traffic. Furthermore, they can enable human operators to remotely monitor, re-task and access data collected by the R-AUVs. R-AUVS can also support the initial phases of exploration and data collection for identification of promising exploitation areas.

Beyond providing energy, communications and data storage services, Undersea Support-Infrastructure (USI) for R-AUVs offers an opportunity for introducing autonomy functions to plan, coordinate and execute operations with multiple R-AUVs. Monitoring and maintenance services for the R-AUVs themselves can be integrated as services supported by the USI directly. Due to the requirement for unmanned operations,

 ISBN: 978-1-61208-787-0

the USI must be able to autonomously interact with and provide services to the R-AUVs. Additionally, it must allow *human-on-the-loop* operations, where a human operator remotely supervises and directs, when necessary, IMR activities. Similarly to the R-AUVs, the USI must operate autonomously while striving to accomplish the service provisioning goals and objectives defined by the operator.

This paper proposes the Human-on-the-loop Autonomy in Austere Networking Environments (HANEn) architecture, a new autonomy architecture for the USI that emphasizes planning, resource allocation and service provisioning for R-AUVs as they perform IMR activities. The operational scenario discussed herein focuses on situations where communications with a human operator are unreliable and intermittent. Similar to the MORPH architecture for self-adapting systems [4], HANEn allows for reconfiguration of subsystem parameters, and redefinition of service and behavior policies. Additionally, it features dual and cooperative Planning Layers that extend the classical three-layer architectures to accommodate the spatial dimension associated with coordinating activities across multiple USIs. Due to the inherent risks associated with undersea operations, HANEn must support fault diagnostics and management services for the USI. Furthermore, fault diagnostics services can be provided to the R-AUVs by the USI directly or as remotely-operated service managed by the operator. These services can be implemented within HANEn via the definition of appropriate configuration strategies, e.g., use redundant hardware when necessary, and behavior policies, e.g., redefine the quality-of-service provisioning provided to R-AUVs as a function of the degradation experienced by the USI hardware components.

HANEn proposes a four-layer architecture for autonomy whose fourth layer, called the Global Planning Layer, resides with the operator, outside the USI; supports multiple and concurrent USI deployments; enables planning functions to use models, policies and historical data collected from multiple USIs; and, provides an interface for the human operator to monitor and direct USIs and by extension the R-AUVs. The Local and Global Planning Layers are connected through an unreliable, low-bandwidth and high-latency communications network. One of the main implications of this separation is that the *perceived* state of the USI and its environment is not necessarily the same when seen from the Local and Global Planning Layers. Thus, modeling and inference tools become fundamental for maintaining alignment between the operator's and the USI's understanding of the state of the USI and the environment in which it operates.

The paper is organized as follows. Section II provides an overview of the HANEn Architecture. Section III describes the configuration strategy and behavior policy selection at each layer of the HANEn four-layer architecture and their interaction with the Knowledge Repositories. Section IV discusses how HANEn enables regional coordination for provisioning of IMR services to support management of oil and gas subsea infrastructure. The paper concludes in Section V.

II. HANEn Architecture Overview

In this section, the HANEn autonomy architecture is introduced. HANEn builds on the Monitor, Analyze, Plan and Execute over a Knowledge-Base (MAPE-K) model and proposes a four-layer architecture for implementing the Analyze and Plan computational modules [18]. MAPE-K defines four fundamental modules used to model the decision making process of autonomous and self-adapting systems as a control loop, namely the Monitor (M), Analyze (A), Plan (P), Execute (E) modules (see Fig. 1). Additionally, MAPE-K also features the Knowledge Repository (K) containing environment, system and goal models, inference and learning tools, and data logging and managing capabilities. Its content is available to all MAPE-K modules and layers of the decision-making hierarchy defining the Analyze and Plan modules. Our four-layer architecture introduces the Operational, Control, Local Planning and Global Planning Layers, thereby extending the three-layer architectures often used as the basis for developing autonomy architectures for self-adapting and autonomic systems with an additional planning layer [2], [4], [12], [13], [14], [16]. The Global Planning Layer can be understood as a global planning and knowledge aggregation layer bridging mutiple, otherwise disconnected, USIs as shown in Fig. 1. An overview diagram of HANEn that highlights its relationship with MAPE-K modules is shown in Fig. 2.

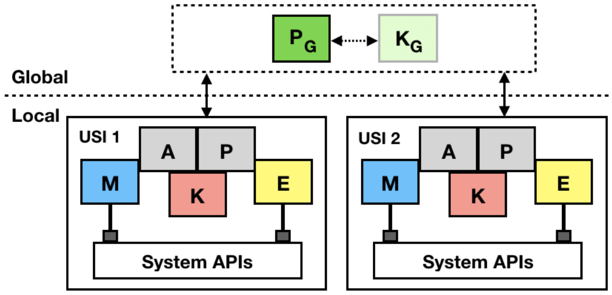

Figure 1. HANEn architecture modeled via an extended MAPE-K model featuring local M, A, P, E, and K modules interacting with the USI via its Application Programming Interfaces (APIs). It also illustrates the global Planning (P_G) and Knowledge Repositories (K_G) that enable HANEn to coordinate activities across multiple USIs.

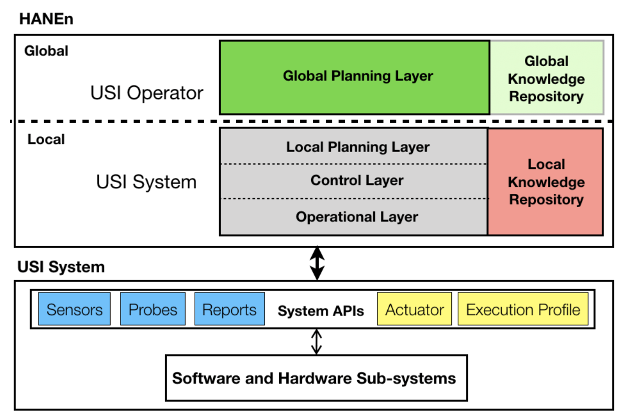

Figure 2. Block-diagram representation of the HANEn Architecture for a single operator-USI pair. Block colors used therein correspond to those used in the MAPE-K modules shown in Figure 1.

The motivation behind implementing a classical three-layer architecture for the Analyze and Plan modules within MAPE-K is the realization that decision making in any autonomous system must occur at different time scales and use different system-state definitions [2], [3], [14]. Three-layer architectures

 ISBN: 978-1-61208-787-0

have remained relevant in the past decade as is noted by their usage for modeling recent cloud-based robotics and self adapting systems. These systems presume the availability of reliable, high-bandwidth communications between the Control Layer implemented in individual robots and the Planning Layer instantiated in a cloud computing platform [2], [22]. In that context, it is natural to implement regional Planning Layers at locations that have powerful computational resources and large sets of data and models available, rather than at individual, resource-limited robots [9]. In this case, the regional Planning Layer is continually updated with data and policy updates received from individual robots and able to support advanced, computationally-intensive inference procedures.

The four-layer architecture used by HANEn continues to separate decision making according to the timeliness and state information with which decisions must be made. This separation highlights the different *knowledge* requirements for the various levels of configuration strategy and behavior policy definition needed by the USI. The Global Planning Layer in HANEn enables the USI to use the data, models and computational resources that the USI has available via the Local (K) and Global (K_G) Knowledge Repositories, respectively (see Fig. 2). It thereby addresses the need for managing access and usage of intermittent global data and computational resources, and USI-operator directives to optimize the local and global performance of multiple USIs. Furthermore, it enables planning and execution coordination of concurrent operations among multiple USI deployments.

A brief description of HANEn and the USI systems it supports is given in the following subsections.

A. System

The USI system is the combination of controllable and observable hardware and software elements that provide support and services to the R-AUVs. It comprises all sensors and actuators that the USI uses to monitor and direct the system to provide services and execute actions. The policies and configuration options selected for the system by HANEn are constrained by the capabilities implemented in the USI and the availability of Application Programming Interfaces (APIs) to access them. From an autonomy architecture vantage point, the system provides monitoring and control mechanisms through a collection of APIs. These APIs provide access to all relevant USI subsystems. The monitoring mechanisms available in the system include the generation of status updates and event notifications, and access to raw and processed sensor data. Control mechanisms available in the system include the configuration of actuator parameters and the definition of service execution profiles.

B. Operational Layer

The Operational Layer is concerned with execution, monitoring, and enforcement of configuration and behavior policies as defined by the Plan and Control Layers. Events handled by this layer require rapid response to either maintain or recover a specific system state. The configuration strategies and behavior policies used by this layer are defined by the Control Layer. It reacts directly to data collected by the Monitor module through sensors, software probes, and status and fault reports generated by the system, and creates status and event reports for the upper layers. It also commands reconfiguration of system parameters and behavior policies via the Actuator and Execution Profile system APIs, and reports system faults and anomalies to the Control Layer.

C. Control Layer

The Control Layer is concerned with the reconfiguration of parameters and behaviors of the system components using precomputed configuration strategies and behavior policies that can be used in response to system state changes. Behavior policies can be generated via dynamic resource management and scheduling algorithms. Reconfiguration can be triggered by a request from the Planning Layer to accommodate a change in the USI goals, or a notification from the Operational Layer in response to a fault or anomaly identified in the system. Behavior reconfiguration can also be triggered by the Control Layer itself to resolve issues that would prevent the system from achieving the goals defined in the Goal Model, or capitalize on opportunities identified thru *knowledge* available in the Knowledge Repository. The latter may occur, e.g., when verifying that the assumptions under which current behaviors enacted by the Operational Layer are still valid. This layer receives new configuration strategies and behavior policies from the Local Planning Layer, and can request new configuration strategies and behavior policies when suitable ones are unavailable.

D. Local Planning Layer

The Local Planning Layer resides with the USI. It is responsible for all long-term planning activities. It defines behavior policies and corresponding system-parameter configuration strategies to support policy execution. Configuration strategies and behavior policies are chosen to satisfy the system goals defined by the operator. This layer is responsible for translating the system goals provided by the operator to a goal model that links goal satisfaction with specific system configuration and behavior requirements. Not only do goal models support the definition of long-term configuration strategies and behavior policies, but they also enable the system to identify configurations and behaviors necessary for accomplishing the system goals. The resulting set of requirements are used by this layer to define configuration strategies and behavior policies.

The Local Planning Layer relies on the state and evolution models, goal models, learning and policies database available in the local Knowledge Repository. New configuration strategies and behaviors can be triggered by requests from the Control Layer, or internally by changes in the Goal Model or the definition of new behavior policies through internal learning mechanisms. This layer checks for consistency between the behaviors and the configuration to ensure that behavior execution can be conducted as expected. Reconfiguration strategies also include safe-transition approaches to reach a given system configuration (state) given the current system configuration and behavior policies, and the environment's state.

E. Global Planning Layer

The Global Planning Layer resides with the human operator infrastructure. It includes a human-machine interface (HMI) module that the USI operator can use to monitor and manage the system remotely. When connected to the USI, it can supersede the Local Planning Layer Goal Model, configuration strategy and behavior policy definition mechanisms according to the Authority Management Functions responsible for planning decision-authority allocation. HADEn's human-on-the-loop autonomy enables the operator to demand decision-control over the system to define configuration strategies, behavior policies and force the execution of specific actions by directly interacting with the system APIs. The Authority Management Functions enable the operator to gain and relinquish control of the system via the HMI, and to reallocate decision authority over the system to the Local Planning Layer whenever the USI loses connectivity with the operator. The Global and Local Planning Layers use a collection of authority tokens to identify and track who has authority over the system. These tokens are stored in the Knowledge Repository and are managed by the Planning Layers directly.

The Global Planning Layer has access to the Global Knowledge Repository that subsumes historical data collected across a variety of USI deployments and configurations. Thus, it can, in principle, develop well-informed configuration strategies and behavior policies to enable USI and R-AUV coordination across multiple USIs, specially when compared with those developed by a single USI using its own, local Knowledge Repository. It, furthermore, can exercise case-based reasoning to transfer configurations and behaviors learned in one USI to address a similar challenge arising in a different USI.

F. Knowledge Repository

The Knowledge Repository is a resource shared by all computational blocks of HADEn. It decouples the data- and information-aggregation activities from the decision-making activities enacted by the selection of configuration strategies and behavior policies. The Knowledge Repository is responsible for logging and storage of system data and system reports. These data are used by the inference and learning blocks. The inference block uses data to update models for the environment, the USI and the R-AUVs. These models are used by the decision making layers to verify that the assumptions behind the active behavior policies are valid. Data are also used by internal learning mechanisms that attempt to develop new behavior policies. The resulting policies can be enacted by the Local Planning Layer or used to extend the Global Knowledge Repository, which is available to the USI operator. The Goal Model defined in the Knowledge Repository, together with the models of the USI, the environment and the R-AUVs, are used by the Planning and Control Layers to assess whether the requirements for goal completion are satisfied.

The Knowledge Repository is divided between the USI operator and the individual USI. In scenarios with intermittent and unreliable communications between the operator and the USI, it is not practical to synchronize the content of the Global and Local Knowledge Repositories. Instead the content of the local Knowledge Repository can be summarized via model abstractions, compressed data, report representations, and information summaries that will be sent periodically to the global Knowledge Repository residing with the USI operator, whenever communication opportunities are available.

III. Decision-Making Structure and Support

The layering approach featured by HANEn implements the separation-of-concerns design principle to manage the different time scales and information requirements of the decision making processes executed within each USI, and globally across multiple USIs. When executing their internal decision making process, each layer is only concerned with requests and reports coming from the layer below, and directives in the form of new configuration strategies and behavior policies from the layer above. Additionally, each layer uses specific content and functions from the Local Knowledge Repository to verify the context in which the decision making process is taking place. The four-layer autonomy architecture used by HANEn can be modeled as a hierarchical control system implementing loosely coupled, dual MAPE-K models in the Operational and Control Layers, as shown in Figure 3, and single MAPE-K models in the Local and Global Planning Layers each having access to related, yet different, Knowledge Repositories, as shown in Figure 4.

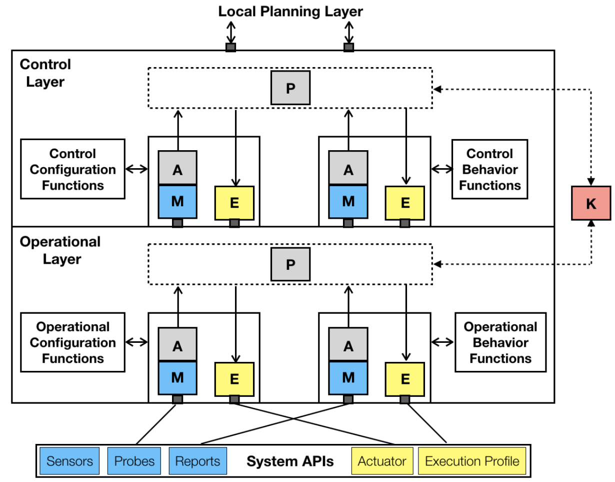

Figure 3. Internal configuration of the Operational and Control Layers, both of which have access to the Local Knowledge Repository (K). Plan (P) Modules in each layer act as arbitrators between the configuration and behavior functions to define the appropriate autonomy strategy to follow.

The Operational and Control Layers are modeled via two MAPE-K models that monitor, maintain, and select the configuration strategy and behavior policy approaches used. Each Monitor and Analyze block-pair is responsible for collecting and analyzing configuration and behavior-specific data in the form of reports, requests, time-series, et cetera. Each layer implements a set of configuration and behavior functions that support the Analyze and Plan computational blocks within the layer. Per layer, the MAPE-K models share a common Planning computational block and have access to the local Knowledge Repository. In addition to deciding what configuration strategies and behavior policies to deploy, the Planning block decides how new configuration strategies and behavior policies are to be deployed and executed based on the analysis provided by the two Analyze blocks in the layer. Its role includes deciding whether the configuration strategies can support the execution of a given behavior policies, whether a change in the configuration affects the viability of the current behavior policy, and what the transition approach for new configurations and behaviors must be to avoid inadvertently driving the system configuration into an execution pitfall that would affect the ability of the system to achieve its goals.

The Local and Global Planning Layers are responsible

ISBN: 978-1-61208-787-0

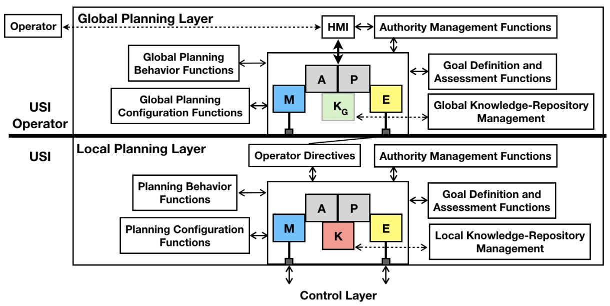

Figure 4. Internal configuration of the Global and Local Planning Layers. The Local (Global) Knowledge Repository is colored red (green) and denoted by K (K_G). Note that K and K_G do not necessarily have the same content.

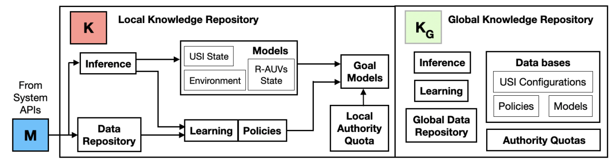

Figure 5. Internal configuration of the Local and Global Knowledge Repositories.

for long-term planning and adaptation functions. The Local Planning Layer uses its configuration and behavior functions to define new configuration strategies and behavior policies. Updates occur whenever the USI encounters situations that cannot lead to accomplishing the USI goals given the *known* configuration and behavior strategies available in the local Knowledge Repository. This layer receives operational directives from the Operator through the Global Planning Layer, which could pass the directives directly to the USI or use its Global Knowledge Repository and up-to-date information about the USI to define a goal model for the specific USI to achieve. When directives are shared with the USI, the USI uses its Local Knowledge Repository to define a goal model that links goals with USI system requirements in a hierarchical and logical structure. The Goal Model and a set of appropriate assessment metrics are then stored and maintained in the Local Knowledge Repository. They serve as the basis for the configuration strategy and behavior policy evaluation conducted by the Control and Operational Layers.

The Global Planning Layer has similar decision-making responsibilities to those of the Local Planning Layer. It, however, features two major differences with respect to its local counterpart. First, it has access to the Global Knowledge Repository and, thus, to a larger set of information records, knowledge, and presumably more advanced data inference capabilities. This repository has records of historical data, configuration strategies, behavior policies, and models collected over time, across all USIs managed by the operator. In addition to its responsibilities with each USI, the Global Planning Layer is responsible for coordinating activities across USIs for all regional energy, data storage, communications and R-AUV services. Second, it offers an HMI for the operator to interact with the USIs. This interface allows the operator to monitor and direct individual USIs and coordinate operations across all regional USIs. The HMI uses the Global Knowledge Repository and the inference and forecasting tools available within it to present the status of a given USI and its environment to the operator. In most situations the global Knowledge Repository will not have access to the raw data captured by a USI, thus the state view offered to the operator is based on model abstractions and summary updates that an individual USI can transmit to the operator.

The Local and Global Planning Layers also share the set of authority management functions that assign and manage the *authority tokens*, defining who has authority over a given USI, i.e., what Analyze and Plan computational blocks will be used by the USI to define new configuration strategies and behavior policies. The default operational mode of HANEn is configured for human-on-the-loop operations. Thus, the operator, through the Global Planning Layer, has a default supervisory role with the USI having ownership of its authority token. When the operator and the USI are connected, the operator can request an authority transfer to direct USI operations. When the authority token is assigned to the operator, the Local Planning Layer has the responsibility of monitoring its connectivity with the operator, to promptly regain authority over the USI if connectivity with the operator is lost for a predefined length of time. The Authority Quota knowledge structures in the global and local Knowledge Repositories allow the operator and the USIs to track authority ownerships. They could also define finer authority control over specific USI functions to support the implementation of adjustable autonomy strategies [5], [19].

Finally, the Planning Layers are responsible for managing the Local and Global Knowledge Repositories content, see Fig. 5. Data and model management policies are defined and enforced by the Knowledge-Repository Management block. These include data prioritization policies for exchanging data between local and global Knowledge Repositories, and data expiration policies that define when USI data logged in the Local and Global Knowledge Repositories can be archived or discarded. The Knowledge-Repository Management block is also responsible for defining behavior policies for the communication interface that connect the USI and the operator. Behavior policies include data-exchange schedules, allocation of communication resources, data summarization, data compression policies, and security postures.

IV. Regional Planning Coordination

This section discusses regional planning coordination using HANEn to support a group of USI deployments, where each USI deployment is responsible for a group of R-AUVs supporting IMR operations for an Undersea Oil and Gas Infrastructure (OGI). In this scenario, the Regional USI Operator and the OGI Manager are considered different and not necessarily co-located roles. For instance, the USI Operator could be part of an infrastructure-as-a-service provider for undersea operations, while the OGI Manager is a member of an oil and gas management company. Therefore, the scenario considered here depicts an Internet Service Provider (ISP) network connecting the USI Operator and the OGI Manager. Both the USI Operator and the OGI Manager use private networks to access and manage their infrastructure. Figure 6 shows the USIs, R-AUVs and other OGI interacting in support of an IMR mission.

Upon receiving a request from the undersea OGI Manager for periodic inspections, the regional USI Operator updates the schedule of operations for the R-AUVs available in its

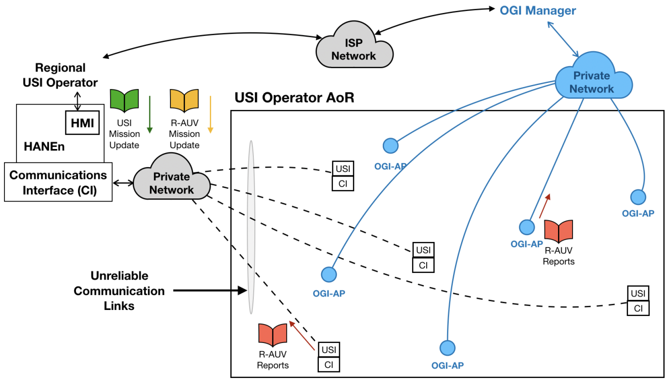

Figure 6. Sample HANEn deployment to support IMR operations for undersea OGI. The OGI is managed and monitored by the OGI Manager via OGI Access Points (OGI-APs). The regional USI Operator provides directives to the USI and R-AUVs via the HMI offered by HANEn.

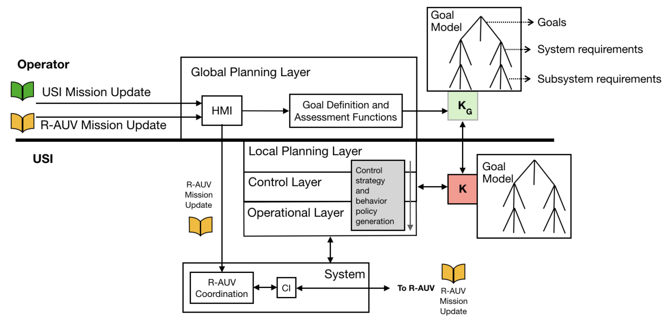

Figure 7. Goal Model generation based on a USI mission update introduced by the operator, and transfer of R-AUV mission updates via the USI.

area of responsibility (AoR). The R-AUV service schedule implicitly defines a baseline schedule of operations for the USIs in the same AoR. The USI Operator uses the HANEn HMI interface to upload USI mission updates. Then, HANEn creates an updated Goal Model within each USI that aligns with the new mission objectives. This model is created by the Global Planning Layer and stored in the Global Knowledge Repository. Then, it is transferred to an individual USI where it is maintained in their Local Knowledge Repositories. The updated Goal Model triggers a review of schedules and resource-usage profiles within each USI to verify that the currently available configuration strategies and behavior policies can support the new service profiles required by the R-AUVs given the current USI state. The operator also notifies mission and configuration updates to the R-AUVs via the USI. Updates for the R-AUVs are passed via HANEn as a *mission update file* for the R-AUV USI subsystem, which is responsible for coordinating local interactions with R-AUVs and relaying operation directives from the operator to the R-AUVs. Note that in this case the authority token remains with the USI. Figure 7 illustrates the goal-model generation and R-AUV mission update process.

After conducting their missions, R-AUVs upload data and inspection reports generated during the mission to the USI. The USI is responsible for transmitting the data gathered by the R-AUVs to the Regional USI Operator who is in turn responsible for generating an inspection report for the OGI Manager. R-AUVs also upload detailed resource utilization summaries to the USI Operator who uses them for service-billing purposes.

The OGI Manager is able to remotely monitor and manage some elements of the OGI infrastructure via strategically positioned OGI Access Points (OGI-APs). These OGI-APs enable the OGI Manager to identify and respond to anomalies and faults that require additional inspection, or on-site intervention and repair. The OGI Manager sends *urgent* service requests to the Regional USI Operator who sends updated mission directives to a selected group of R-AUVs to support the OGI Manager IMR request. Mission updates are also sent to each USI to guarantee that the updated service profile for the R-AUVs can be supported, see Figure 7.

Mission updates for the USIs and R-AUVs are transmitted over a network whose *last-mile* communications link is intermittent and unreliable. Thus, the Global Planning Layer of HANEn must carefully manage the allocation of communication resources between the operator and the USIs. These resources and their configuration are controlled directly via the local API for the Communications Interface (CI) available to the operator. The USIs have a similar management responsibility over their local CIs for managing their communications with the Regional USI Operator.

In some cases, the OGI Manager may not be able or willing to tolerate the long delay that the data collected by the R-AUVs will incur when being transmitted to the OGI Manager via the Regional USI Operator network. In this case, the latency experienced by the data aggregates both the latency due to delays and disruption in the network between the USI operator and the USIs, and the R-AUV transit time back to the USI prior to the data being delivered to it. In those cases, the R-AUVs could use the OGI-APs to upload their data and report directly to the OGI Manager. Not only could this approach reduce the overall R-AUV data latencies, but it could also give R-AUVs access to a more reliable communications infrastructure that will allow them to upload larger volumes of sensor and actuator data to the OGI Manager. Behavior policies executed on the USI Operational Layer are responsible for managing the data gathered by the R-AUVs either as backup copies of the data sent directly to the OGI Manager or as redundant data that can eventually be discarded.

V. Conclusions and Future Work

This paper proposed HANEn, a new autonomy architecture for USI supporting R-AUV missions. HANEn enables human-on-the-loop operations and is well-suited for scenarios where the communications between the operator and the USI are intermittent, and characterized by low bandwidth and high latency. USIs using HANEn can operate autonomously, while still allowing the operator to gain control over them as needed. HANEn features a four-layer autonomy architecture whose fourth layer, the Global Planning Layer, supports coordination among multiple USIs, management of regional Knowledge Repositories, and an HMI that enables observability and controllability of the USI by an operator. A key benefit achieved by the Global Planning Layer is the persistent regional USI management which is achieved by the effective use of the Global Knowledge Repository and the inference tools embedded in it. HANEn's layered architectural approach separates the decision-making processes that are conducted by the USI according to their required execution time scales. Furthermore,

 ISBN: 978-1-61208-787-0

it separates the selection of configuration strategies and behavior policies, thereby isolating configuration and functionality concerns. The use of HANEn was discussed within the context of IMR missions for OGI.

Future work will focus on the development of a notional HANEn implementation with emphasis on the engineering aspects of the Local and Global Planning Layers, and the interaction between HANEn and the R-AUVs. As a layered architecture, HANEn could naturally extend various self-adaptive autonomy architectures, such as MORPH, and enable systems using them to coordinate activities across a common Global Planning Layer. Prior implementations of three-layer autonomy architectures can be used as a starting point for developing *local* USI autonomy. One of the major implementation challenges for HANEn lies on the *intelligent* use of the communications and networking capabilities available to connect the USI with the operator and the R-AUVs. Communications in the maritime domain are not reliable, often offer limited and variable communication bandwidths, and are sensitive to environmental conditions. Synchronization of the Local and Global Knowledge Repositories in such operating environment may be impractical if HANEn were to, e.g., attempt to synchronize raw sensor-data recordings. Our initial implementation approach relies on the use of high-resolution parametric models and bounded knowledge-graph structures that can provide sufficient information to support the reasoning and inference functions needed at the Global and Local Planning Layers of HANEn.

Finally, careful implementation of the Authority Management Functions both on the Local and Global Planning Layers is critical to avoid execution pitfalls in which the USI is unable to regain authority over some or all of its functions, even when the operator is disconnected from the USI. The Authority Management Functions are critical for HANEn to enable the operator to control the USI. Thus, they require special safeguards to be put in place to enable the Local Planning Layer to regain control over the USI. Similarly and from the operator's vantage point, authority token allocations should be resilient to instabilities in the communications path between the operator and the USI to avoid unnecessary authority token transfers and the corresponding decision-making reallocations needed as part of such transitions.

ACKNOWLEDGEMENT

This work was funded by the Naval Innovative Science and Engineering program at the Naval Information Warfare Center Pacific.

REFERENCES

[1] E. Ackerman, "The underwater transformer: Ex-NASA engineers built a robot sub that transforms into a skilled humanoid," *IEEE Spectrum*, vol. 56, no. 8, pp. 22–29, Aug 2019.

[2] A. Ahmad and M. A. Babar, "Software architectures for robotic systems," *J. Syst. Softw.*, vol. 122, no. C, pp. 16–39, Dec. 2016.

[3] R. Alami, R. Chatila, S. Fleury, M. Ghallab, and F. Ingrand, "An architecture for autonomy," *The International Journal of Robotics Research*, vol. 17, no. 4, pp. 315–337, 1998.

[4] V. Braberman, N. D'Ippolito, J. Kramer, D. Sykes, and S. Uchitel, "MORPH: A reference architecture for configuration and behaviour self-adaptation," in *Proc. of the 1st International Workshop on Control Theory for Software Engineering*, ser. CTSE 2015. New York, NY, USA: ACM, 2015, pp. 9–16.

[5] C. Calefato, R. Montanari, and F. Tesauri, "The adaptive automation design," in *Human Computer Interaction: New Developments*, K. Asai, Ed. Rijeka: IntechOpen, 2008, pp. 141–154.

[6] M. A. Charette and W. Smith, "The volume of Earth's ocean," *Oceanography*, vol. 23, pp. 112–114, June 2010.

[7] M. Chitre, S. Shahabudeen, L. Freitag, and M. Stojanovic, "Recent advances in underwater acoustic communications networking," in *IEEE OCEANS*, Sep. 15-18, Quebec City, Canada 2008, pp. 1–10.

[8] N. A. Cruz, A. C. Matos, R. M. Almeida, and B. M. Ferreira, "A lightweight docking station for a hovering AUV," in *IEEE Underwater Technology*, Feb. 21-24, Busan, South Korea 2017, pp. 1–7.

[9] D. Weyns et al., "On patterns for decentralized control in self-adaptive systems," in *Software Engineering for Self-Adaptive Systems II: International Seminar, Dagstuhl Castle, Germany, October 24-29, 2010 Revised Selected and Invited Papers*, R. de Lemos, H. Giese, H. A. Müller, and M. Shaw, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2013, pp. 76–107.

[10] S. Fan, C. Liu, B. Li, Y. Xu, and W. Xu, "AUV docking based on USBL navigation and vision guidance," *Journal of Marine Science and Technology*, vol. 24, no. 3, pp. 673–685, Sep 2019.

[11] M. Furuholmen, A. Hanssen, R. Carter, K. Hatlen, and J. Siesjo, "Resident autonomous underwater vehicle systems – a review of drivers, applications, and integration options for the subsea oil and gas market," in *Proc. of the 11th Offshore Mediterranean Conference*, Mar. 20-22, Ravenna, Italy 2013, pp. 387–395.

[12] D. Garlan, S.-W. Cheng, A.-C. Huang, B. Schmerl, and P. Steenkiste, "Rainbow: architecture-based self-adaptation with reusable infrastructure," *IEEE Computer*, vol. 37, no. 10, pp. 46–54, Oct 2004.

[13] D. Garlan and B. Schmerl, "Model-based adaptation for self-healing systems," in *Proc. of the First Workshop on Self-healing Systems*, ser. WOSS '02. New York, NY, USA: ACM, 2002, pp. 27–32.

[14] E. Gat, "Three-layer architectures," in *Artificial Intelligence and Mobile Robots*, D. Kortenkamp, R. P. Bonasso, and R. Murphy, Eds. Cambridge, MA, USA: MIT Press, 1998, pp. 195–210.

[15] B. Gilmour, G. Niccum, and T. O'Donnell, "Field resident AUV systems – Chevron's long-term goal for AUV development," in *IEEE/OES Autonomous Underwater Vehicles*, Sep. 24-27, Southampton, United Kingdom 2012, pp. 1–5.

[16] D. Goldberg, "Huxley: A flexible robot control architecture for autonomous underwater vehicles," in *IEEE OCEANS*, June 6-9, Santander, Spain 2011, pp. 1–10.

[17] T. Hyakudome, "Design of autonomous underwater vehicle," *International Journal of Advanced Robotic Systems*, vol. 8, no. 1, p. 9, 2011.

[18] J. O. Kephart and D. M. Chess, "The vision of autonomic computing," *Computer*, vol. 36, no. 1, pp. 41–50, Jan 2003.

[19] M. Luck, M. D'Inverno, and S. Munroe, "Autonomy: Variable and generative," in *Agent Autonomy*, H. Hexmoor, C. Castelfranchi, and R. Falcone, Eds. Boston, MA: Springer US, 2003, pp. 11–28.

[20] T. Matsuda, T. Maki, K. Masuda, and T. Sakamaki, "Resident autonomous underwater vehicle: Underwater system for prolonged and continuous monitoring based at a seafloor station," *Robotics and Autonomous Systems*, vol. 120, p. 103231, 2019.

[21] R. B. Wynn et al., "Autonomous underwater vehicles (AUVs): Their past, present and future contributions to the advancement of marine geoscience," *Marine Geology*, vol. 352, pp. 451–468, 2014, 50th Anniversary Special Issue.

[22] O. Saha and P. Dasgupta, "A comprehensive survey of recent trends in cloud robotics architectures and applications," *Robotics*, vol. 7, no. 3: 47, 2018.

[23] J. Sverdrup-Thygeson, E. Kelasidi, K. Y. Pettersen, and J. T. Gravdahl, "The underwater swimming manipulator - a bio-inspired AUV," in *IEEE/OES Autonomous Underwater Vehicles (AUV)*, Nov. 6-9, Tokyo, Japan 2016, pp. 387–395.

[24] T. Ura, "AUV "r2D4", its operation, and road map for AUV development," in *Advances in Unmanned Marine Vehicles*, ser. Control, Robotics and Sensors. Institution of Engineering and Technology, 2006, pp. 239–254.

 ISBN: 978-1-61208-787-0